Effluent Fate Study
Lahaina Wastewater Reclamation Facility
Maui, Hawaii

Final Report

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TETRA TECH

Executive Summary

Background

A fluorometric survey of an area of the near coastal waters of western Maui, offshore from the Lahaina Wastewater Reclamation Facility (LWRF) was conducted in August 1993 to determine the fate of the effluent from the LWRF. Effluent is currently injected into four wells drilled to maximum depths of 180-255 ft below the ground surface and located approximately 600 m (2,000 ft) inland from the shoreline. The effluent is assumed to discharge into the near coastal waters. This study was prompted by concerns of suspected causal links between nutrients in the effluent and previous algal blooms reported along the west Maui coastline. The study was conducted at the request of Region 9 of the U.S. Environmental Protection Agency (USEPA) in conjunction with the Environmental Planning Office of the Department of Health of the State of Hawaii, and the Wastewater Reclamation Division of the County of Maui. These agencies are investigating possible land-based hydrologic sources that may be contributing excess nutrient loadings into the coastal waters of western Maui.

The primary objectives of this field study were to investigate the fate of wastewater from the LWRF injection wells, to determine the offshore locations of detectable discharges, and to measure the dispersal of the effluent in the offshore waters. A limited number of water samples from the study area were also collected to characterize the nutrient levels in the vicinity of the LWRF.

In order to achieve these objectives, an artificial tracer was added to the effluent as it flowed into one of four injection wells at the LWRF. The tracer chosen was Rhodamine WT, a fluorescent dye that can be continuously sampled and analyzed in the field. This dye does not occur in the natural environment. It can be detected at dilutions of between 10^3 and 10^4 of the input concentration, adsorbs only weakly to sediments, and is chemically stable in the ground water system.

The study design took into consideration the hydrologic characteristics of western Maui and predictions of the transport time, transport paths, mixing, and dilution of the LWRF effluent within the ground water and in the coastal waters. An area of approximately 3,000 m by 3,000 m immediately offshore from the LWRF was investigated. The intent was to locate and map locations of seeps or plumes of dye and effluent entering the coastal waters and to investigate the rates of dilution in the water column. Discrete near-bottom water samples were collected to determine the nutrient characteristics of the effluent after reaching the coastal waters. Water column profile data were also collected.

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Field Activities

Field operations commenced on July 1, 1993 with the first addition of fluorescent tracer to the effluent at the LWRF Injection Well No. 2. Slugs of approximately 9.5 L of 20 percent Rhodamine WT were added to the effluent every eight hours for three days. Continuous addition of tracer to Well No. 2 started on July 2, at a rate of 5 mL/min (7.5 L/day), and continued with occasional interruptions until August 28, 1993. Preliminary monitoring, to detect the initial tracer slugs in the near shore waters was conducted on eight days during the period July 3 - 12, 1993.

The main survey effort began on August 21, after 52 days of tracer injection at Well No. 2, and was completed on August 31, 1993. Over sixty hours of continuous fluorometry data were recorded along 36 transects spaced 100 m apart. Near-bottom fluorometry and temperature readings were taken at approximately 450 locations within the study area. Water samples were collected from 30 locations in the study area and at six reference locations outside the area. These samples were analyzed for salinity and eight nutrients. Twenty-two CTD casts were completed, resulting in water column profiles of temperature, salinity and density versus depth.

The final phase of the field effort started on October 10, 1993 and was completed on December 8, 1993. A total of 80 discrete near-bottom water samples were collected from ten locations within the study area approximately once every week for this period. The samples were analyzed in the laboratory for fluorescence in an attempt to detect the tracer should the residence time within the ground water system be greater than 60 days.

Lahaina Wastewater Reclamation Facility Operations

Normal operations were reported at the LWRF during the period of dye injection and field monitoring. Daily flows were recorded from the flow meter installed at the splitter box immediately up-flow from Well No. 2. Total daily effluent volumes passing through the facility were recorded from a flow meter located at the chlorination contact chamber. Effluent volumes injected into Well No. 2 averaged 3.0 million gallons per day (mgd). The total effluent injected into all the wells at the Facility averaged 5.6 mgd during the study period.

Summary of Findings

The major results of the study are summarized below:

The detection limit of the fluorometer was 0.02 ppb under the existing field conditions. For the tracer, Rhodamine WT, to be present but undetectable in the sampled water, dilutions of the tracer and the effluent of at least 3,200 to 5,900 times would be required.

Nutrient analyses showed mostly uniform concentration distributions with some elevated values. However, there was no correlation between nutrients at the locations of the peak fluorescence values, and no correlation between the occasional elevated nutrient concentrations and the spacial distribution of fluorescence could be identified.

Water column profile data showed nearly constant salinity with depth and approximately one degree Celsius temperature variation between the surface and bottom. These data indicated that the water was well mixed and no thermocline or trapping layer was present.

Background fluorescence concentrations varied between 0.04 and 0.06 ppb within the study area and at the reference stations. Concentrations between 0.01 and 0.3 ppb were recorded frequently in near-bottom water during the first half of the survey, but after investigation these readings were attributed to a light backscattering effect, a result of sand and smaller particles passing through the fluorometer. This source of interference was eliminated in the second half of the survey by installing two extra filters in the water intake line. Once the filters were installed, only a few samples with concentrations above 0.10 ppb were recorded.

Concentrations of near-bottom fluorescence generally fell within the range of the background variations, resulting in a data set with a small signal-to-noise ratio. Statistical analyses and contouring of the data identified five possible areas of elevated concentrations. However, at three of the areas the magnitude of the concentrations was close to the sensitivity limit of the fluorometer, and the fourth signal, although stronger, was a single reading of short duration. At the fifth area, in the southeast corner of the study area and approximately 300 m offshore, concentrations of three times background were recorded at two single but adjacent locations on two different days. The location is at the southern boundary of the study area in about 30 m of water. Freshwater seeps and bubbles had been previously reported in this area, but much closer to the shore in very shallow water (less than 2 m). Further investigation would be required in this area to confirm the presence of elevated tracer and effluent concentrations.

The following conclusions can be drawn from the results of the study:

- Elevated concentrations of tracer were recorded at five near-bottom areas within the study area. However, these readings of between 0.02 to 0.12 ppb above the background concentration were either at the limit of sensitivity of the instrumentation or were recorded for very short durations. Consequently, it can not be stated conclusively that the tracer was present at the time of sampling. Further intensive sampling would be required at each of the five locations to verify the presence of elevated effluent concentrations.

- At all other areas within the study area, the tracer was not detected. For the tracer to be present and undetectable, the tracer and the effluent with which it was mixed, must have undergone dilutions of between 3,200 and 5,900 times the injection concentrations. If the tracer was present at detectable levels, it was diluted below detection concentrations before reaching any sampling points, or it was present during times that sampling was not being conducted at that area. If it was present in the near-bottom water, the tracer had been diluted to undetectable concentrations vertically within the first 10 to 30 cm of the bottom, or horizontally within 100 to 200 m of its seabed source.

- The probability of tracer entering the coastal waters within the study area as a single plume is very low. It is more likely that if the tracer was present, it influxes through a large number of discrete points or through one or more wide-area seeps at low flow rates.

- No correlation is evident between the fluorometric survey results and the nutrient analyses or the long-term post-survey fluorescence analyses.

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1.0 Overview

A field study was conducted during July and August, 1993, to investigate the fate of the Lahaina Wastewater Reclamation Facility (LWRF) effluent. This investigation was prompted by concerns over the occurrence of nuisance green algal blooms during the spring and summer months of some years in the near-shore waters of western Maui (Figures 1-1, 1-2). The field study was conducted at the request of Region 9 of the U.S. Environmental Protection Agency (USEPA) in conjunction with the Environmental Planning Office of the Department of Health of the State of Hawaii and the Wastewater Reclamation Division of the County of Maui. These agencies are investigating possible land-based hydrologic sources that may be contributing excess nutrient loadings into the coastal waters of western Maui. The LWRF injection wells were thought to be a possible source of nutrients because municipal sewage effluent has high nutrient concentrations, and this effluent is assumed to be released to the marine environment, possibly elevating concentrations of nitrogen and phosphorus in the nearshore waters. Approximately five million gallons per day (mgd) of secondary treated effluent are injected into four wells at the facility. The effluent is believed to discharge into saline ground water below the basal ground water lens and approximately 100 ft below the surface.

The purpose of the field study was to determine if the LWRF effluent could be detected in the nearshore waters, and if so, to determine the locations, areal extent, and peak concentrations of the effluent plumes or seeps. Nutrient concentrations in the vicinity of the effluent influxes and estimates of the dilution rates of the effluent within the receiving waters were also measured.

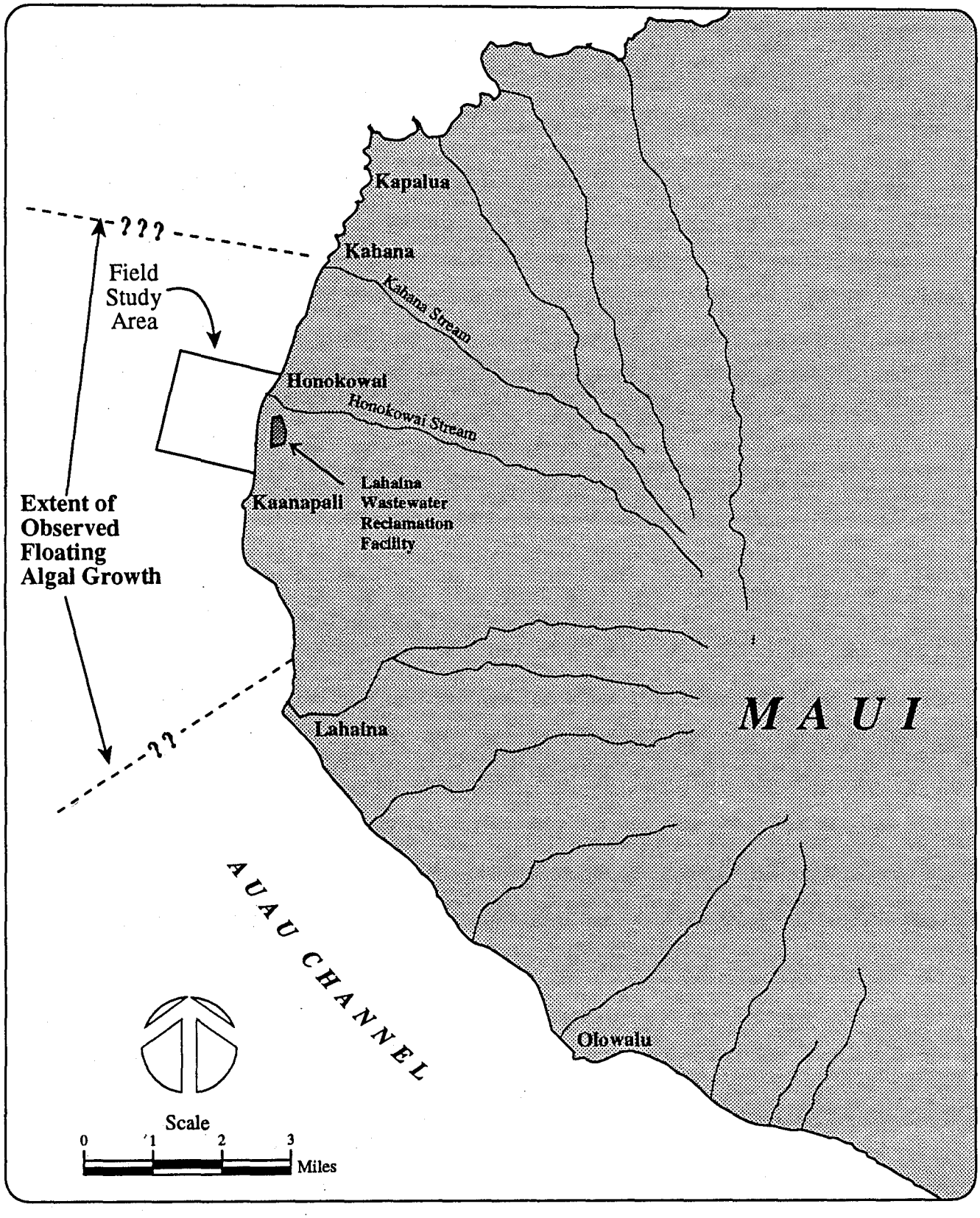

Figure 1-2. Location of Lahaina Wastewater Reclamation Facility and field study area on the Island of Maui.

2.0 Historical Studies

Although many studies have been completed on the fate of sewage effluent discharged from municipal wastewater treatment plants into marine environments, few relate to effluent discharge via injection wells. A summary of previous studies and discussion of treatment facilities using subsurface wastewater effluent disposal methods are provided in Tetra Tech (1993a). Marine discharge via subsurface injection does not appear to be a common disposal method (Metcalf and Eddy, 1979). This disposal method has become common in Hawaii, although the main application is in shallow small-scale septic treatment systems that are common in coastal tourist areas (Oberdorfer and Peterson, 1982). A modeling study conducted for the Wailuku-Kahului Wastewater Treatment Facility (Burnham et al., 1977), located on the northeast coast of Maui, approximately 25 miles from the LWRF, indicated that the effluent would rise through the saline ground water and ultimately discharge into the coastal waters. Although previous investigators presumed the results of the Kahului study applied to the LWRF effluent, it is unclear whether the results can be extrapolated to the LWRF effluent, given the hydrologic differences between the sites.

A summary and statistical analyses of coastal water monitoring data collected at ten monitoring sites in the Lahaina area between August 1990 and July 1992 are provided in Tetra Tech (1993b). The reported nutrient concentrations, which were collected very close to the shore in knee-deep water, were somewhat elevated relative to general ocean waters because of the proximity to the shoreline. Stream and nearshore water nutrient parameters measured by Grigg (1983) during a storm, represent a five-year flood event. Water quality data were collected during the summer of 1990 in the nearshore waters off the Kaanapali Golf Course, between Black Rock (Kekaa Pt.) and the LWRF (Dollar, 1991).

3.0 Study Design

In order to investigate the fate of effluent from the LWRF, a field study was designed to detect the occurrence of effluent in the nearshore waters at dilutions of up to 10,000 times the injected effluent. The study design was based on the addition to the effluent, prior to injection, of an artificial fluorescent dye, which could be detected in seawater at the anticipated dilutions. In response to the uncertainties surrounding the fate of the injected effluent, a sequential set of objectives were developed for this field program:

1. Determine if the tracer (and therefore the injected effluent) can be detected in the nearshore waters.

2. Define the areal extent and maximum tracer concentrations of the effluent plume(s).

3. Locate the effluent seeps on the seafloor.

4. Measure the tracer concentrations at the seafloor source(s) and the dilution within the water column.

5. Determine the maximum measurable nutrient concentrations in the vicinity of the seafloor sources.

Two secondary objectives were also developed:

1. Monitor the coastal waters immediately after adding the tracer to determine the transit time of the tracer and effluent from the injection well, through the ground water, and into the ocean water.

2. Periodically monitor the coastal waters, after the completion of the detailed field effort, to detect the arrival of the tracer if it was not detected previously.

Because of the extent of uncertainty associated with the effluent discharge characteristics, it was recognized that these objectives might not be achieved, and if any objective was not achieved, the subsequent objectives could not be achieved. The study design included these considerations and was constructed such that minimum dilutions of the tracer and effluent could be determined even if none of the objectives were attained.

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The rationale for the sampling design was based on information presented in earlier Tetra Tech reports (1993a, b). This information was used to evaluate several discharge scenarios and two "worse-case" scenarios:

- an effluent plume resulting from influx into coastal waters from a single point source
- a wide-area extensive seep, at low velocity, which would remain close to the seafloor.

Between these two extreme cases lie a continuum of discharge situations, ranging from a small number of discrete influx points, with associated and proportionately smaller plumes, to a number of seeps of effluent of various sizes and flow rates, to a combination of both point and seep discharges.

Several distinct design components required consideration. The type and amount of tracer, the residence time in the ground water system, dilution in the coastal water system, the characteristics of the receiving water, the size of the study area, the number and density of sampling points, and the probability of detecting an effluent plume of a given size if it was present in the study area. These design parameters are discussed in more detail below.

3.1 Tracer

After consideration of several alternatives (Tetra Tech 1993a), a fluorescent dye, Intracid Rhodamine WT (Crompton & Knowles, Reading, PA.), was chosen as a tracer for the effluent. Rhodamine WT was chosen because it is the weakest adsorbing of the commonly used fluorescent tracers and it is chemically stable in the natural subsurface environment. Gaspar (1987) referred to Rhodamine WT as the tracer of choice for ground water studies. Rhodamine WT has been used extensively in both ground water and marine water applications, and it is commonly used to trace sewage in distribution lines, sewers, and treatment plants.

Although Rhodamine WT is used commonly as a tracer in marine and estuarine circulation, dilution, or dispersion studies, and in sewage and effluent infiltration or rate-of-flow studies, the usual periods for which the studies are conducted are a few hours to a few days. For this LWRF effluent fate study, dye was injected almost continuously for 59 days and monitoring continued for 53 days from the start of dye addition. Research into previous studies of the behavior of Rhodamine WT dye in chlorinated effluent and marine environments were made as part of the field study design (Tetra Tech, 1993a). Only two relevant studies, Deaner (1973) and Smart and Laidlaw (1977), were identified. Deaner (1973) examined the effects of chlorine on fluorescent dyes, including Rhodamine WT,

in laboratory tests. Smart and Laidlaw (1977), compiled results from earlier studies, including Deaner (1973), that investigated the loss of fluorescence of Rhodamine WT and other fluorescent tracers as a result of different processes. The processes included the effects of heat, light, chlorine, chloride, and adsorption.

The loss of fluorescence as a result of oxidation reactions between Rhodamine WT and the residual chlorine present in the effluent appeared to be the most likely source of loss of tracer in this study, and this effect was investigated further. After an extensive literature search, no reports of field tests using dyes were identified. Because of the wide variation in effluent characteristics, especially between wastewater treatment facilities, and because of the complex dissipation characteristics of chlorine within the effluent stream, laboratory testing can only approximate expected rates of chlorine dissipation and fluorescence reduction.

Many studies have been conducted on the dissipation of chlorine added to wastewater treatment plant effluent, power station cooling waters, or seawater (Lee, 1979; Goldman et al., 1979; Hostgaard-Jensen et al., 1977; Johnson, 1977; Fava and Thompson, 1977, Eppley et al., 1976). Cooling water can be expected to be a more conservative model of effluent, in terms of residual chlorine dissipation rates, because of the naturally occurring lower concentrations of organic and inorganic matter and suspended solids found in estuarine and marine waters, the common sources of cooling waters. For both cooling waters and wastewater effluent, levels of residual chlorine concentrations at the discharge point are of environmental concern and are generally limited to less than 2 mg/L (Metcalf and Eddy, 1979; Hostgaard-Jensen et al., 1977)

Chlorine undergoes a two-part breakdown after addition to the water or effluent. The first is a fast reaction, dependent on the initial concentration of chlorine added, the temperature, and the chlorine demand, which is a function of the concentrations of all the reducing agents present (Lee, 1979; Goldman et al., 1979). As chlorine (free chlorine) is added to the wastewater within the chlorine contact chamber, hypochlorous acid (HOCl) and hypochlorite ions (OCl^-) are formed, which in turn react rapidly with readily oxidizable substances (e.g., H_2S, Fe^{2+}, Mn^{2+}, NO^{2-}) and organic matter to reduce most of the chlorine to chloride ions. Subsequently, the chlorine reacts with ammonia to form chloramines (NH_2Cl, $NHCl_2$), which are less reactive but more persistent oxidizing agents (Metcalf and Eddy, 1979). This second part is a slower reaction, controlled mainly by the rate of dilution of the effluent in the receiving waters.

Evaluations of the effect of residual chlorine levels on Rhodamine WT in chlorine contact chambers have been reported by Deaner (1973) and Smart and Laidlaw (1977). Deaner concludes, from

laboratory studies using samples of activated sludge effluent containing suspended solid concentrations between 15 and 40 mg/L, that

> "Chlorine has little effect on the fluorescence of the dyes Rhodamine B and Rhodamine WT at chlorine residuals normally found in practice (2 to 9 mg/L). This conclusion reflects the long-term, steady-state condition when dye and chlorine are mixed instantaneously."

Deaner's data show a continuous and rapid loss of fluorescence that is proportional to the chlorine residual concentrations. A single rate of loss could not be determined because of the simultaneous dissipation of residual chlorine from the samples. Figure 3-1 shows a plot of data (Deaner, 1973) for two chlorine residual concentrations (2.3 and 4.5 mg/L) and a dye concentration of 10 µg/L for the 20-hour period of the study. For these residual chlorine concentrations (which were between four and seven times the reported chlorine residuals at the LWRF), the measured dye losses were 3.0 and 2.1 percent, respectively, after 20 hours. Other data collected during the same study showed that residual chlorine concentrations of up to 9 mg/L resulted in a similar small loss of fluorescence (less than five percent). At higher chlorine residual concentrations (13 to 43 mg/L), loss of fluorescence increased markedly. However, such high residuals are not typical.

Tests performed on a single sample of chlorinated LWRF effluent sent to Tetra Tech indicated that approximately a 5 percent loss of fluorescence occurred over a 48-day period. However, a loss of residual chlorine may have occurred in the 5 or 6 days between collection of the sample and the addition of the dye. Thus, the results may not be indicative of those expected on-site because of the time delay and other general environmental conditions, such as aeration, mixing, temperature, passage through the ground, etc., which cannot be replicated in the laboratory.

Because of sparse literature on the oxidation of Rhodamine WT dye by residual chlorine, and the concerns raised, Tetra Tech initiated a series of long-term tests by adding measured doses of chlorine and dye to locally available unchlorinated effluent collected from the Central Contra Costa Sanitary District (CCCSD) treatment facility. A series of chlorine doses (from 5.25 mg/L to 63.0 mg/L) was added to the effluent within 2 hours of collection. A 50 µg/L concentration of Rhodamine WT was added to each of the test solutions 30 minutes after the addition of the chlorine dose. The reductions of fluorescence in the test solutions were measured over a 36-day period. Measurements were made frequently during the first 2 days when the rate of change of fluorescence was greatest. Results from the test (Figure 3.2) were similar to those reported by Deaner (1973)for residual chlorine concentrations.

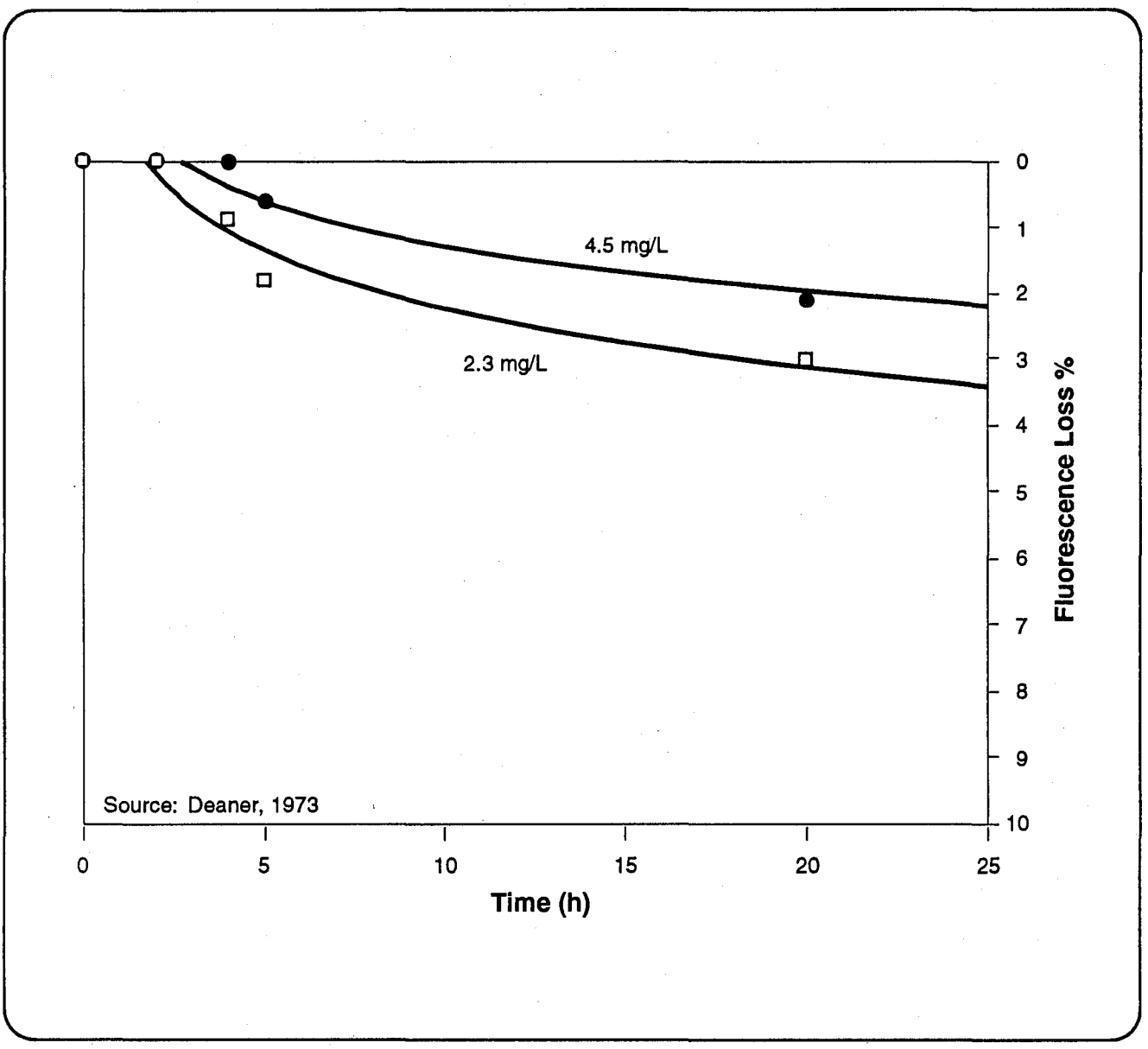

Figure 3-1. Fluorescence loss over time for two initial chlorine residual concentrations.

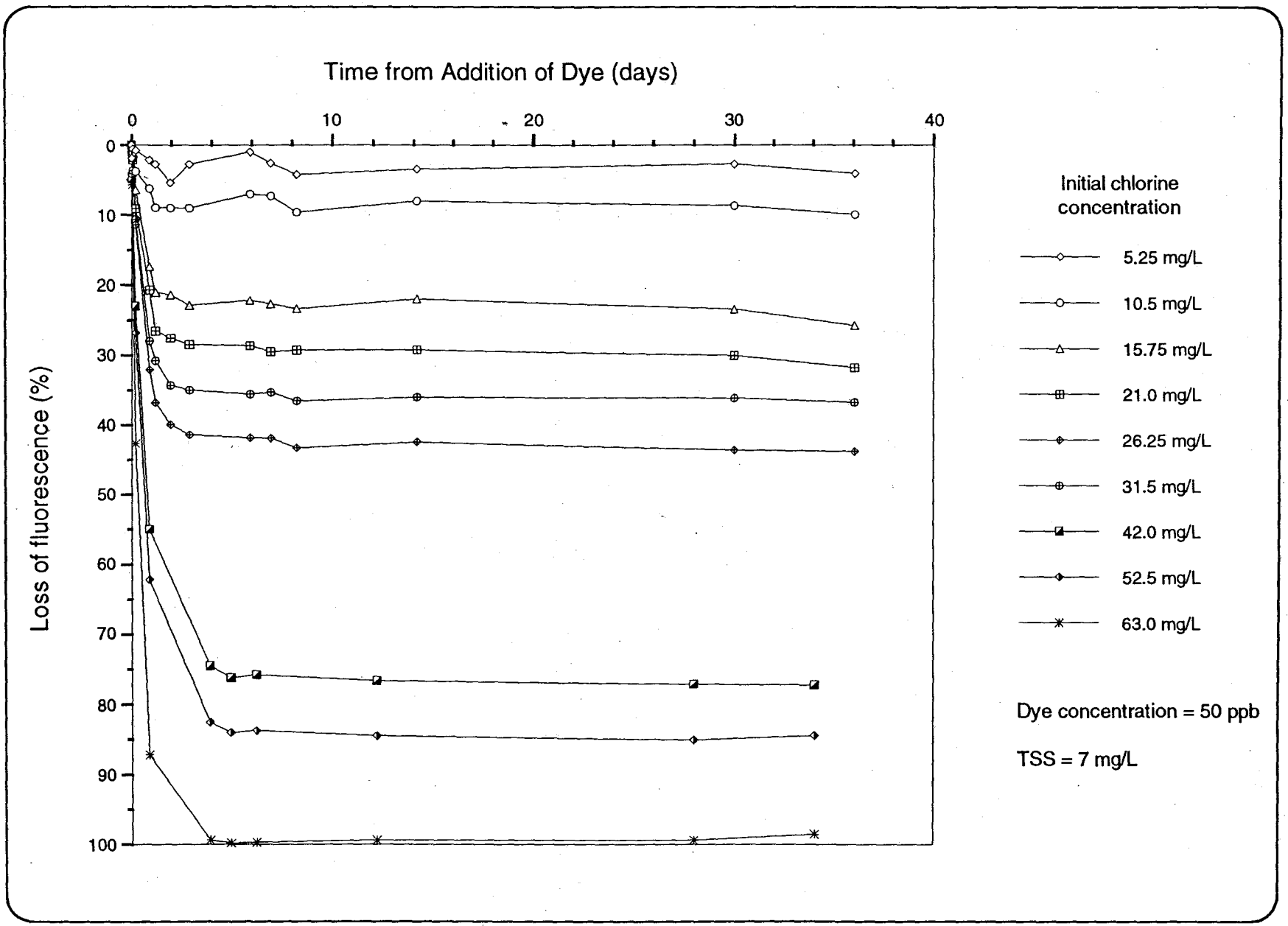

Figure 3-2. Fluorescence loss over time for various initial chlorine doses.

For applied chlorine doses of 5.25 and 10.5 mg/L, the observed loss of fluorescence was less than 5 and 10 percent, respectively. For higher applied chlorine concentrations, the loss or quenching was also higher, ranging from approximately 20 percent for 15.75 mg/L to 85 percent for 52.5 mg/L. At an applied dose of 63.0 mg/L, fluorescence was almost completely quenched. The majority of the quenching occurred within the first 48 hr in all cases. After this time, the loss of fluorescence decreases rapidly and the level stabilized through the remainder of the test.

At the LWRF, the daily applied chlorine dose ranged from 300 to 350 lb, equivalent to 12 - 14 mg/L at an average flow of 3.0 mgd at the 1985 facility. The total residual chlorine was reported between 0.1 and 0.6 mg/L (County of Maui, June 23, 1992), although concentrations of 2 mg/L or greater could have existed during periods of low flow (J. Oka, personal communication, October 12, 1993). In comparison, at the CCCSD facility, an average applied chlorine dose of 27 mg/L produces an average residual chlorine concentration of 11 mg/L (CCCSD, 1993).

The relationship between applied chlorine dose and the subsequent residual chlorine concentration depends upon the chlorine demand from the organic content and from the ammonia present in the effluent. These parameters for the LWRF effluent and CCCSD effluent are:

	LWRF	CCCSD
Applied Cl_2 dose (mg/L)	12 - 14	27
Residual Cl_2 (mg/L)	<0.1 - 0.6	11
BOD_5 (mg/L)	<1.0 - 2.6	3 - 7
Ammonia-nitrogen (mg/L)	0.05 - 0.36	10.8 - 17.6

For CCCSD wastewater, an initial dose of 31.5 mg/L resulted in a maximum loss of fluorescence of about 35 percent (Figure 3.2). From the data (CCCSD, 1993), this applied dose would result in an initial residual concentration of about 11 mg/L, which is between one and two orders of magnitude greater than the LWRF residual values. This suggests that residual chlorine concentration of 11 mg/L would result in a loss of fluorescence of about 35 percent.

The reduction in fluorescence due to a lower residual chlorine concentration of 0.1 - 0.6 mg/L would be expected to be significantly lower than compared to a 11 mg/L residual. While the quantification of chlorine residuals was beyond the scope of this test, several lower applied chlorine doses (from 26.25 to 5.25 mg/L) were tested in order to simulate residual chlorine concentrations of less than

11 mg/L. The long-term reduction of fluorescence was less than 10 percent for the 10.5 mg/L dose and further decreased to less than 5 percent for the 5.25 mg/L dose (Figure 3.2).

Although manufacturers report that chlorine can oxidize Rhodamine WT and diminish fluorescence, technical representatives and laboratory personnel of the manufacturers could not supply specific details on oxidation rates and concentrations. Staff at Pylam Products Company, Inc. (Garden City, NY), reported that chlorine will eventually bleach Rhodamine WT, but no specific concentrations, or rates were available. Laboratory staff at Keystone Aniline Corporation (Chicago, IL), noted that the product specification sheet stated that Rhodamine WT is oxidized by commercially available bleach with a chlorine concentration of 5.25 percent. A laboratory supervisor at Crompton and Knowles' Industrial Products Division (Gibraltar, PA), reported that fluorescence can be diminished, but he could supply only anecdotal evidence of such events (J. MacGill, personal communication, October 12, 1993). An authority from Turner Design, the manufacturer of the fluorometers used in the field study, indicated that although Rhodamine WT can be oxidized, it is not likely to occur to a significant extent at chlorine levels found in effluent (M. Mokelke, personal communication, October 11, 1993).

Rhodamine WT is used frequently for tracer studies in both ground water, marine, and estuarine investigations, although the period of study is usually considerably shorter than for this effluent fate study. From the data presented in the studies and the test discussed above, it appears that although high concentrations of free and residual chlorine can oxidize Rhodamine WT significantly, the levels of residual chlorine commonly found in wastewater treatment practice will have only a minor effect on the fluorescence of the dye. Because of the rapid dissipation of the chlorine residual, extended contact of the dye with the chlorinated effluent is not expected to result in any significant dye loss beyond that which occurs within the first 24 hours. Residual chlorine doses of less than 10 mg/L appear to cause a loss of fluorescence of Rhodamine WT of less than 10 percent.

Based on the studies discussed and considering the complex dissipation paths of the residual chlorine within the LWRF effluent, it was concluded that at normal operating concentrations of less than 2 mg/L, the resulting overall decrease of fluorescence was less than 10 percent over the 60-day period of dye addition. As well, once the effluent is pumped into the ground water, competition for chlorine is thought to increase due to the presence of other particles and organic matter. The rate of chlorine dissipation will increase also and the oxidizing effect on the dye will be decreased. Section 5 addresses the consequences of this possible loss of fluorescence to dye and nutrient detection.

Rhodamine WT is not a refractory tracer, and therefore losses can occur as a result of mechanisms other than oxidation by chlorine. Common mechanisms are photolysis and adsorption. In this study,

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photolysis loss is unlikely to be significantly because the effluent is injected into the ground immediately after addition of the dye. Rhodamine WT has the lowest rate of adsorption of the commonly used tracers, but the rate of adsorption of the dye in the ground is unknown. Previous studies have shown adsorption to be greater in clay material than in coarser materials (Gaspar, 1987). The high rate of flow of effluent into the LWRF wells and the regional geology both indicate that clay-like materials are not prevalent. However, some adsorption of dye is expected to occur, and it is expected to be proportional to the travel time of the dye underground.

3.2 Receiving Water Characteristics

Several features of the coastal and ground water systems in the Lahaina area may influence the fate of the LWRF effluent. The following ground water and coastal waters characteristics were considered in the design of the sampling plan:

3.2.1 Ground Water

- Inland from the coast, the ground water system is classified as an unconfined basal aquifer that is comprised of horizontally extensive lavas on the flank of the West Maui volcano.

- Along the coastline, the aquifer is classified as an unconfined basal aquifer, comprised of sedimentary materials deposited in a narrow strip along the coastline.

- The ground water velocity in the lavas is roughly 17 m/day (56 ft/day) (Tetra Tech, 1993b). Lower velocities are likely in the sedimentary materials.

- The permeable coastal sediments were assumed not to confine the basal ground waters, and vertical movement of the ground water through adjacent strata was not expected to be impeded. Large ground water discharges were expected as a result.

- Because of the unconfined nature of the basal aquifer, the high permeability of both the lavas and the sediments, and the apparent vertical communication through the layered beds, the natural ground water discharge zones were not expected to extend great distances offshore.

- The regional coastal ground water flow has been estimated at approximately 3 mgd/mile. The roughly 4.5 mgd of LWRF effluent was assumed to spread out laterally along the coastline a maximum of 1.5 miles (4.5 mgd ÷ 3 mgd/mile), assuming the effluent rises

into the regional flow field in the basal lens. Preferential flow paths, which may discharge as "sprouting horns," presented the possibility of the effluent discharging in a much smaller horizontal distance along the coastline.

- The effluent is discharged into Well No. 2 and then into the saline aquifer below the basal aquifer at depths of between 100 and 200 ft (30 - 61 m) below mean sea level; however, the exact discharge depth in Well No. 2 is unknown.

- The depth of water at which the effluent discharges into the ocean is unknown. This will be influenced by factors such as the buoyancy of the wastewater which may cause the wastewater to rise in the ground water, and the dip and layering of the lava beds which may cause the wastewater to remain in deeper strata. It was assumed, however, that the probable unconfined nature of the basal lens on West Maui implied that the vertical layering would not result in beds that restrict vertical flow.

3.2.2 Coastal Waters

The Auau Channel, between Maui and Lanai, has an average maximum depth of about 90 m (50 fathoms). The Pailolo Channel, between Maui and Molokai, reaches depths of approximately 275 m (150 fathoms). Offshore from the LWRF, water depths reach 30 m within 1,000 m of the shore and then increase more slowly to 90 m at 4,500 m (2.5 nm) offshore.

Very little information on current patterns has been reported. Nearshore currents in the Auau Channel have been reported to flow predominantly to the north at speeds of 12-25 cm/s and the longshore current is tidally reversing every 6 hr with an average flow of 13 cm/s (Grigg, 1983). However, close to the shore, current flows are complicated by tidal, wind, and shoreline effects. Offshore, the current was observed to flow to the north at all times and tidal reversals were not obvious.

If the effluent emerges from a single point or small number of points on the seabed, the resulting plume is likely to elongate in a north-south direction due to the prevailing currents. The plume is also likely to extend a greater distance north of the influx location than it will to the south because of these currents. This effect was evident from the results of a dye study performed by Grigg (1983). Under these circumstances, the plume may rise to the bottom of the pycnocline, if one has formed, or the plume may even surface if the discharge zone is a submarine spring.

If the effluent enters the coastal waters from one or several diffuse influx zones, the plume(s) will more likely remain submerged and remain within a few feet of the bottom.

3.3 Dimensions of the Study Area

The determination of the appropriate size of the study area depended not only on environmental parameters within the coastal and ground water systems, but also on operational constraints. For example,

- To detect a wide area seep or a large number of discrete sources, the focus of the sampling must be within 3 to 5 ft (0.9 to 1.5 m) of the bottom, close to where the effluent enters the ocean, because, in this case, the probability of detecting the tracer increases closer to the sea floor.

- To detect plumes of effluent emerging from one or a small number of discrete points, the sampling point separation must be less than the width of the plume, and sampling should extend away from the bottom to increase the probability of detecting such a plume.

- The sampling density will be constrained by the combination of the accuracy of position fixing (± 15 ft [4.6 m]) and the position of the pump intake near the sea floor relative to the vessel (estimated at a maximum of ±150 ft [46 m] in 200 ft [61 m] of water). This implies that a sampling grid density greater than 165 ft (± 50 m) cannot be achieved accurately throughout the whole sampling area.

The maximum depth of the sampling area, 70 m (200 ft), is approximately the same as the maximum injection depth of the wells. Although it is possible that the seaward dip of the strata and the likelihood of impermeable layers within the strata may result in the effluent emerging at depths below the injection depths, the 200-ft isobath was chosen as the seaward limit of the study area. This choice was based on the assumed permeability of the lavas and sediments, the unconfined nature of the basal aquifer, and the buoyancy characteristics of the effluent.

The maximum distance offshore of the 200-ft isobath is approximately 1.5 nm. The sampling area, assuming a maximum effluent injection rate of 4.5 mgd, is estimated to extend along the shoreline no further than 1.5 nm by 1.5 nm (1.7 mi or 2,800 m). This results in a study area of 2.25 sq. nm (7.8 km^2), as shown in Figure 3-3.

3.4 Number of Samples

Sampling was designed to be semidiscrete due to time and equipment constraints and in order to satisfy both possible extremes of effluent discharge characteristics (wide-area seeps or plumes from one or a few point sources). It was estimated that an average of 40 to 50 grid points could be

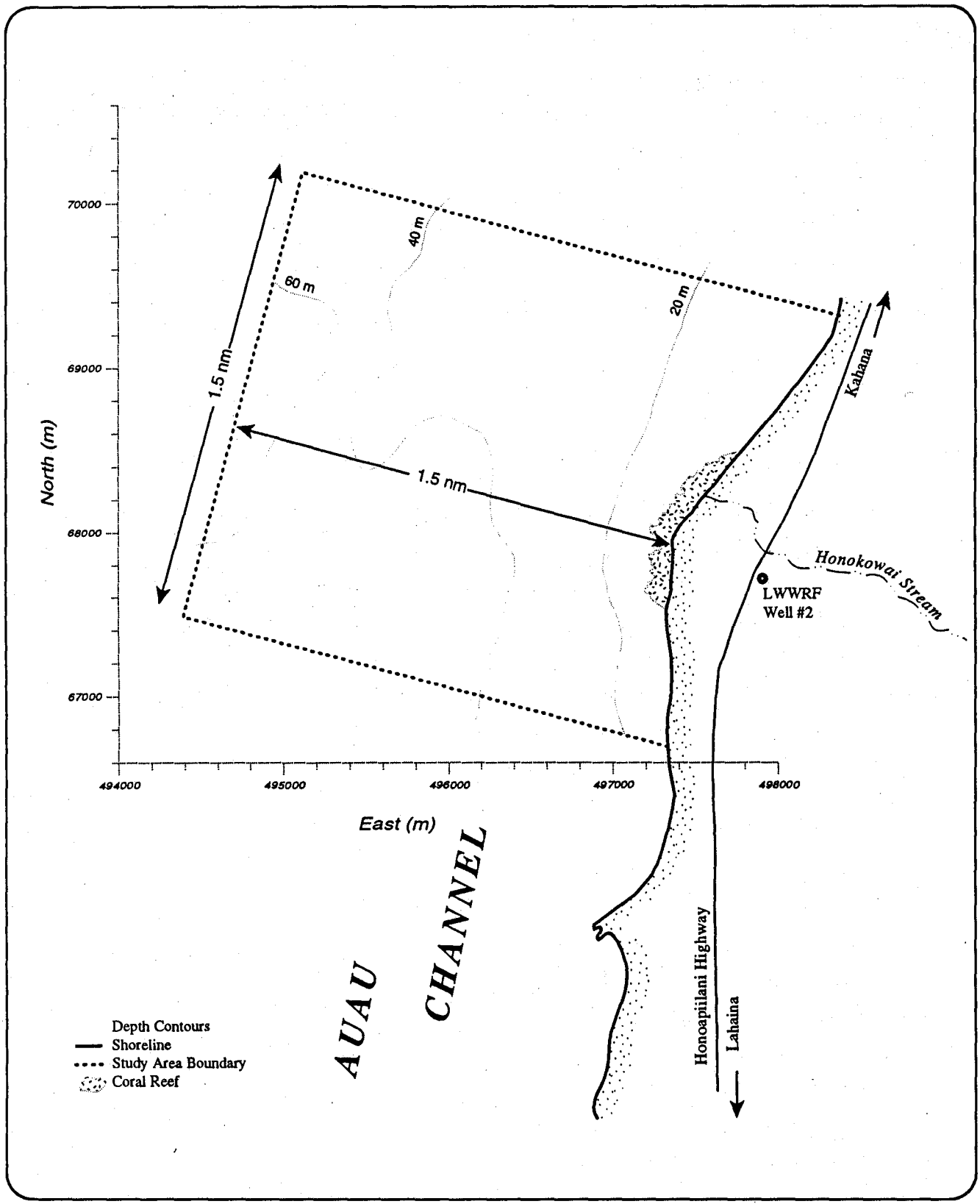

Figure 3-3. Dimensions and location of study area.

sampled each day. A 100-m grid spacing perpendicular to the shore and a 200-m grid spacing parallel to the shore was established. Transects were computed to be 100 m apart and approximately parallel to the shore (Figure 3-4). Near-bottom water samples were measured every 200 m along each transect. Approximately 450 near-bottom water samples were measured.

3.5 Probability of Detection of a Single Plume

The two extremes of possible effluent influx to the coastal waters were considered in the field study plan. For wide area seeps or a large number of discrete vents, the probability of detection would be increased by sampling close to the bottom. For a small number of vents or point sources, the probability of detection would be increased as the density of the sampling grid increased. A sampling design was developed to address both possibilities. Semi-discrete near-bottom sampling was incorporated to improve the detection of wide area seeps. A sampling grid of sufficient density was designed to maximize the detection of the extreme case of discrete sources: a single source and plume entering the coastal waters.

Based on the ground water and coastal water characteristics, it was assumed that if the effluent enters the coastal water as a single plume, it would be oriented parallel to the coastline and elongated in shape. The location at which the discharge occurs is unknown, but the maximum extent along the shoreline is roughly 1.5 miles (2.8 km), centered on the LWRF and based on a diffuse discharge at rates comparable to the regional ground water discharge. In the worst-case scenario of a single plume, the minimum detectable plume width in the direction perpendicular to the nominal current (and also perpendicular to the shoreline) is estimated to be on the order of 400 ft (122 m), based on dilution calculations. This was calculated assuming the plume was vertically mixed over 50 ft of the water column, a 25 cm/s current, 2 kg/day of dye was added to the LWRF effluent, and a variation of at least 0.05 ppb of dye concentration could be detected. A 3-to-1 aspect ratio of length to width was used to estimate a plume length of 1,200 ft. The plume was expected to remain submerged. However, it was recognized that the plume might rise through the water column to the surface.

The probability of detecting the tracer in a wastewater plume of fixed dimensions and from a single source was determined using the method of geometric probabilities. The probability of plume detection for different sized study areas, plume sizes, grid sizes, and numbers of sampling points was calculated according to Gilbert (1987). The computed probability of plume detection for the selected study area size (1.5 nm by 1.5 nm), the estimated single plume size (400 ft by 1,200 ft), and the number of uniformly distributed sampling points (400-500) was between 0.95 and 0.99 (Table 3-1).

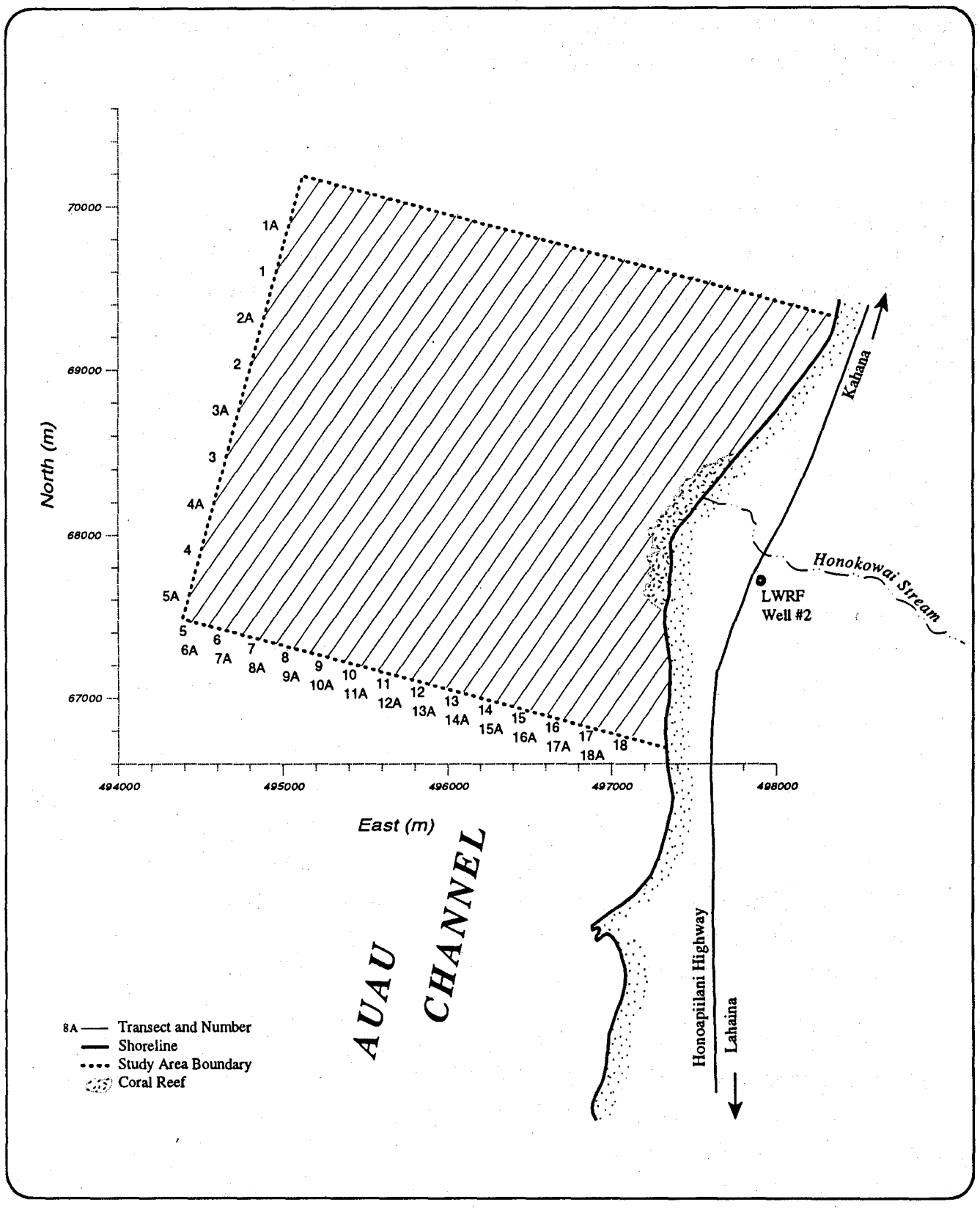

Figure 3-4. Location of survey transects within the study area.

TABLE 3-1. PROBABILITY OF PLUME DETECTION

Study Area	Plume Size (ft)		Number of Samples			
	Plume Size (m)		200	300	**400**	**500**
1.5 x 1.5 nm		**Grid Size (m)**	300 x 150	240 x 120	**200 x 100**	**185 x 90**
2.8 x 2.8 km	80 x 240		0.04	0.05	0.07	0.08
	24 x 73					
	250 x 750		0.29	0.44	0.56	0.68
	76 x 230					
	400 x 1,200		0.65	0.85	**0.95**	0.99
	122 x 366					
	800 x 2,400		0.82	0.99	0.99	0.99
	245 x 732					
	2,500 x 7,500		0.99	0.99	0.99	0.99
	762 x 2,286					
	4,100 x 12,300		0.99	0.99	0.99	0.99
	1,250 x 3,750					

3.6 Nutrient Sampling

Near-bottom water samples were collected at selected stations within the study area and reference stations to the south of the study area. These samples were analyzed at a University of Hawaii laboratory, using high precision methods, for total dissolved nitrogen (TDN), nitrate nitrogen (NO3), ammonium nitrogen (NH4), total dissolved phosphorus (TDP), ortho-phosphate (PO4), dissolved silica (Si), and salinity.

3.7 Water Column Profiling

Conductivity-temperature-depth (CTD) measurements were collected within the study area and at reference stations to determine the depth of the pycnocline where water column stratification begins. Station locations corresponded to every second nutrient sampling station within the study area and to nutrient sampling reference stations.

3.8 LWRF Effluent Flows

Effluent flows were monitored daily by facility personnel. Daily records were kept of the total volume of effluent treated at the facility, and readings were also recorded manually, two or three times a day, from a flow meter at the splitter box above Well No. 2. Calibrated amounts of tracer were added to the Well No. 2 effluent at this splitter box.

3.9 Post-Survey Sampling

Approximately 1 month after the end of the main monitoring effort, discrete water samples were collected from 10 near-bottom locations throughout the study area. These locations were chosen after the initial analysis of the fluorometric survey data had been performed and represented areas of possible elevated readings or other areas of interest, such as a nearshore area in which bubble seeps and freshwater influxes had been previously reported, a station off the mouth of Honokawai Stream, and a station at the deepest part of the study area. Samples were collected approximately every week for 8 weeks and were sent to San Francisco for analysis of fluorescence concentrations.

This part of the survey was carried out to increase the total length of the monitoring period in order to increase the probability of detecting tracer if the residence time of the effluent within the ground water system was greater than the expected period of 50 to 60 days.

4.0 Materials and Methods

The effluent fate field study commenced on July 1, 1993, with the addition of Rhodamine WT to the LWRF effluent injected into Well No. 2. Field work was performed over three periods, a preliminary monitoring effort conducted between July 2 and July 12, 1993, the main survey effort conducted between August 21 and August 31, 1993, and post-survey sampling, conducted approximately weekly between October 10 and December 12, 1993.

4.1 Tracer Addition to LWRF Well

For 3 days, approximately 9.5 L of tracer (a 20 percent solution of Rhodamine WT) were added to the effluent every 8 hours. Starting on July 2, 1993, a constant supply of tracer was also added to the effluent, using a calibrated pump, at an average rate of 5.2 mL/min. This is equivalent to 7.5 L/day of dye solution and 1.5 L/day of active tracer or a concentration of between 70 and 130 ppb. The tracer was added continuously at this rate for 58 days, until August 28, except for brief periods due to pump failure or a delay in the delivery of drums of Rhodamine WT to the LWRF. The lower concentration (70 ppb) was calculated by using the total effluent volume of 5.6 mgd, assuming the effluent injected into all four wells was mixed completely in the ground water system. The higher concentration (130 ppb) was based on an average volume of effluent of 3.0 mgd injected into Well No. 2 alone and assumed no mixing of effluent injected into different wells.

4.2 Preliminary Monitoring

Because of uncertainties in the expected dilution of the effluent and concerns that the transit time through the ground water system might be short (resulting in visible concentrations of tracer appearing in nearshore areas), preliminary monitoring by boat started the day after the first tracer additions. Seven half-day, near-surface monitoring cruises were completed by the 26-ft survey vessel during a 10-day period.

The survey vessel was launched from Mala Wharf small-boat ramp each day and was slipped and stored at the LWRF Pumphouse No. 4 overnight. For the preliminary survey, a Model 10 Analog Field Fluorometer (Turner Designs, Sunnyvale, CA) was used as the monitoring instrument. A 12-volt DC pump was used to deliver water through a 5/8-in hose to the fluorometer. Between 75 and 200 ft of hose were towed behind the vessel as it moved through the survey area. A steel depressor fin and lead weights were attached to the end of the hose, allowing water to be pumped from depths of 20 to 40 ft.

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Problems were encountered with the hose collapsing and with maintaining the end of the hose at depth. It appeared that the hose was not sufficiently rigid to withstand the pressure difference created by the suction of the pump, and as the effective diameter of the hose was decreased, the flow rate decreased. The hose intake could not be maintained at depths greater than 20 to 40 ft because of a number of factors. These included the buoyancy and drag of the hose and the minimum speed of the survey vessel, which was too high to allow the hose to sink further. The fluorometer calibration also appeared to drift markedly on two occasions. As a result, the hose and pump were modified, and the fluorometer was changed for the main survey.

4.3 Mobilization

Mobilization began on August 17 for the main survey. All the survey instrumentation was air-freighted from the mainland and installed on the survey vessel. The instrumentation consisted of a differential Global Positioning System (GPS) navigation system; a digital fluorometer; a digital fathometer; portable computers to interface and record the navigation, depth, and fluorometry signals; and submersible pumps. A 115-volt portable generator and 12-volt marine-use acid batteries were obtained locally.

4.4 Navigation and Bathymetry

As part of the mobilization, a differential GPS reference station was established close to the survey area. The GPS equipment, Trimble 4000 series (Trimble Navigation, Sunnyvale, CA), and MDL telemetry link (MicroTel, Birmingham, England) were used to transfer survey control from a first-order U.S. Geological Survey station, *Laina*, located on Pioneer Mill Company land behind Lahaina, to a location on the roof of the Embassy Suites Hotel, located at the beach between the LWRF and the study area. Once the coordinates of this roof station were calculated, the GPS reference unit was installed at the same roof location and the remote unit and telemetry link were mobilized on the survey vessel.

Transect lines were precomputed for the study area using State Plane Coordinates, Hawaii Zone 2, North American Datum, 1983. Geographic conversions were performed with CORPSCON, computer software published by the U.S. Army Topographic Engineering Center (Ft. Belvoir, VA). After consultation with the captain of the survey vessel, transects were calculated to run parallel to the prevailing wind direction to facilitate vessel handling during sample collection. (Thus, the vessel could travel more slowly and be maneuvered more accurately when heading into the wind.) To cover the study area, 36 transect lines, 100 m apart, and in the direction of 035° - 215° true, were computed, using Trimble HYDRO software (Auckland, New Zealand) (Figure 3-4).

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The same software package was used to interface and record real-time navigation, depth, and fluorometry data. These data were updated every second and were recorded every 15 seconds and upon demand. The data were recorded directly to the hard disk of the portable computer (Toshiba 3200). The computer was also used to monitor all data during the survey and to control a remote monitor installed at the helmsman's position. This monitor provided continuous updates of the position of the vessel as distance along the line and distance off line for each transect.

The majority of sampling stations were occupied and sampled within 50 m of the precomputed coordinates and for all stations the navigation system recorded vessel positions to an accuracy of better than ±5 m. The position of the intake pump on the seafloor, relative to the vessel, was never greater than ±35 m from the recorded position. This difference is a function of the water depth was likely to occur only in depths greater than 40 m and during rough weather, when the wind and waves made it more difficult to hold the vessel steady and on location.

Bathymettic data were measured continuously and recorded every 15 seconds along transects. A MD100 digital fathometer (Meridata, Olhja, Finland), with a resolution of 0.1 m and accuracy of ±0.5 m was interfaced to the navigation computer. A small transducer was mounted on the stern of the vessel. No heave or tidal corrections were applied to the bathymetric data.

4.5 Fluorometric Survey

The main survey of the study area was conducted from August 21 to 31, 1993. Over 60 hours of data collection were completed during 10 cruises. A Model 10-AU-005 Digital Field Fluorometer with temperature compensation (Turner Designs, Sunnyvale, CA) was used in conjunction with the differential GPS navigation system described. The fluorometer was set to update every 2 seconds. The internal data logger in the fluorometer was set to record time, water temperature, and the 3-second moving average of fluorescence. The navigation software recorded time, position, depth, and the instantaneous reading from the fluorometer every 15 seconds.

The limit of detection of the fluorometer was reported to be between 0.01 and 0.05 ppb above background for Rhodamine WT in potable water and 0.1 ppb in raw sewage. (Turner Designs, 1990). The seawater in the study area was clear and low in suspended particulates. Because of this, the field detection limit was estimated to be 0.02 ppb (S. Mokelke, personal communication, January 17, 1994). The temperature sensor accuracy is reported as ±0.2 °C (Turner Designs, 1990). An exponential temperature coefficient of -2.6 percent was used for the automatic temperature compensation of the water flowing through the fluorometer cell. The instrument is designed to measure the rela-

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tive difference in fluorescence between a sample and a calibrated standard concentration and the accuracy of the instrument is directly related to the accuracy of the calibration standard. Three replicate standards of 1.00 ppb and three replicate standards of 10.0 ppb were prepared for the field calibration of the instrument. The variation in the readings for the 1.00 ppb standard was consistently 0.02 to 0.03 ppb. From these results, the accuracy (the measure of the difference between the real reading and the instrument reading) is estimated to be 0.03 ppb.

The fluorometer was calibrated before the beginning of the main survey, after every 2 days, and again at the end of the survey, using a 1.00 µg/L (1 ppb) standard solution of Rhodamine WT and distilled water as a reference blank.

A 115-volt submersible pump, Little Giant Model 3E-12N (Tecumseh Products, Oklahoma City, OK), modified for use in 70 m of water, and contained in a specially designed polyethylene housing, was attached to 250 ft of 1/2-in diameter nylon hose and powered by a 650-watt portable gasoline-powered generator via a three core, 14-gauge electrical cable taped to the hose. A 2.5-mm polypropylene mesh covered the pump intake. An additional 150-denier nylon mesh was installed after sand was detected being pumped through the fluorometer, and an additional in-line 100-micron nylon filter (Pepco, Fresno, CA) was installed in the hose line immediately before the fluorometer.

One-half-inch nylon rope was taped to the hose to act as a strength member and a 15-lb lead weight was attached to the pump to speed its descent through the water column and to help detect when the pump was on the bottom. The weight was originally attached with a short cord, designed to sit on the bottom while the pump remained 30 cm from the bottom. However, in deep water, where a considerable length of hose was required to reach the bottom, it was difficult for the hose operator to discriminate between the weight and the pump hitting the bottom and it is assumed the pump was also on the bottom for the majority of sampling stations. The pump housing prevented the intake of the pump from being closer than 10 cm to the bottom.

All transects, except one, were run in a south to north direction. For the first half of the survey every second transect, numbered from 1 to 18, was run. The alternate transects, numbered 1A through 18A, were run during the second half of the survey (Figure 3-4). The submersible pump was switched on before the beginning of each transect, and data was recorded continuously on both the navigation computer and the internal logger of the fluorometer for the time required to complete each transect.

The vessel stopped at 200-m intervals along the transect line, as close to the line as possible. The pump and hose would sink to the bottom, and as soon as the hose operator determined the pump and weight were on the bottom, time, position, and depth were recorded (in addition to the automatic 15-sec recordings). The vessel remained on station for a minimum of 1.5 min and then moved along the line another 200 m to the next station. Once the vessel started moving, the pump and hose rose close to the surface and sank again after the vessel had stopped. Typically, the pump was on the bottom for 1.5 min, rose through the water column for 30 sec, was near the surface for 1.5 min, and fell through the water column for 1.5 min, creating a sampling cycle of approximately 5 min (Figure 4-1).

The flow rate of the pump was measured at frequent intervals to determine the transit time of water in the hose. This time was generally about 2 min. Data were recorded for an extra 3 min after the end of each transect, to allow for the transit time of the water sample travelling through the hose to the fluorometer. After the final data were recorded, the vessel returned to the southern end of the study area to begin another transect. The pump was either streamed behind the vessel or brought on board for inspection and maintenance of the filters and expansion bladder.

At the end of each survey day, the data collected was downloaded from the navigation computer, copied, and reviewed to verify that data collection had occurred correctly and to determine if spacial patterns of elevated fluorescence had been detected.

At the end of the data collection, the data was analyzed and adjusted for the time lag of the water moving through the 250-ft length of hose from the submersible pump to the fluorometer. The time required for sample water to be pumped through the hose to the fluorometer was approximately 2 min. This required that the fluorometry data be inspected and adjusted with respect to time to correspond with the depth and position data recorded for each sample point. The flow rate of the pump was recorded at regular intervals by recording the length of time required to fill a 2-gallon container. Several discrete water samples were collected from the fluorometer discharge hose at times when elevated concentrations were being recorded. These samples were inspected and analyzed at the end of the day.

Fluorometry data were recorded as a concentration in parts per billion (ppb), relative to the calibration standard. Near-bottom fluorometry values were correlated with respect to time with the depth and position data and then examined for spacial patterns.

Six reference stations were chosen beyond the probable influence of the LWRF effluent influx. All stations were between 4,000 ft and 18,000 ft (1,200 m to 5,500 m) to the south of the study area, at

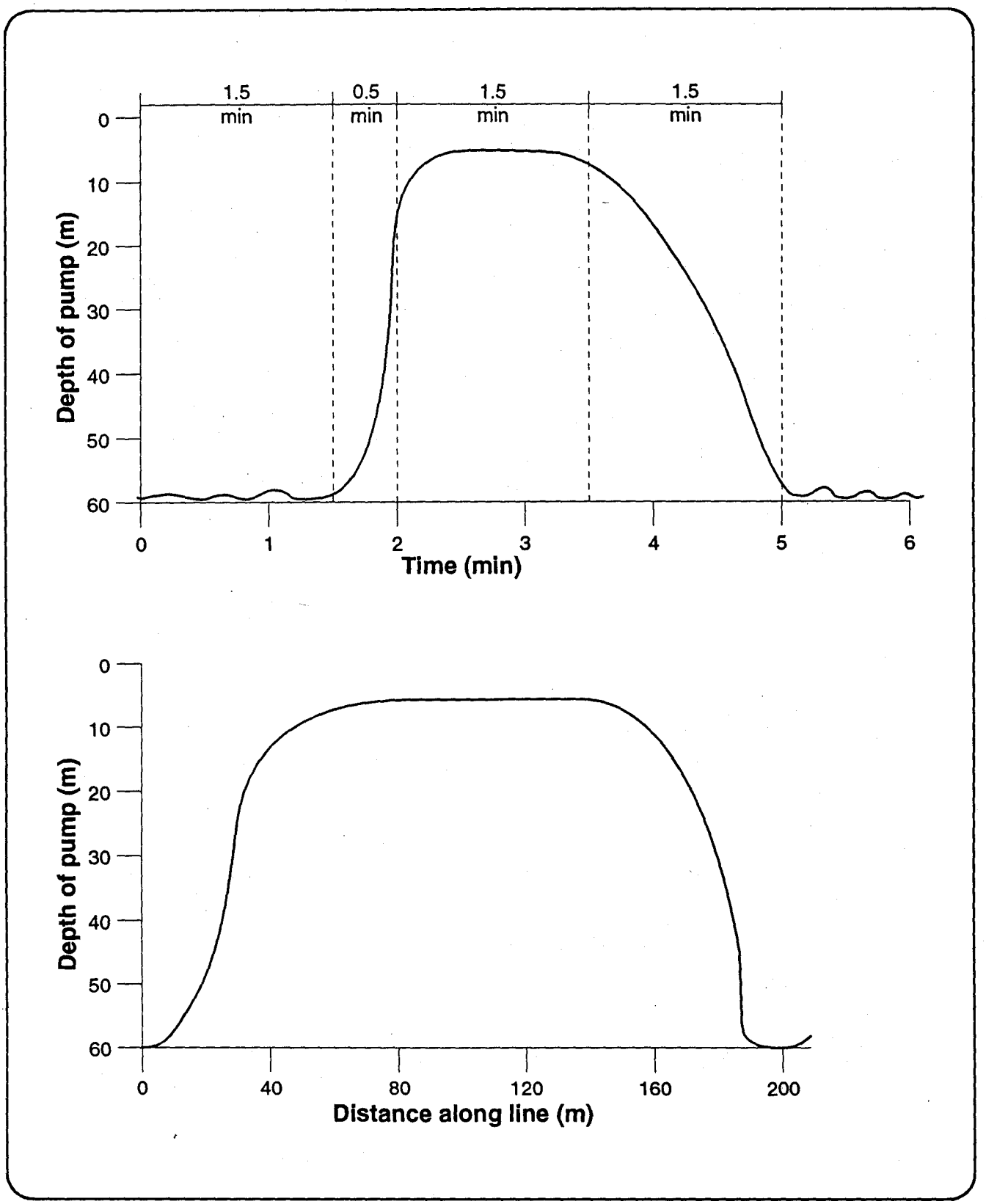

Figure 4-1. Typical pump depth versus time and distance between adjacent sampling stations.

m) apart. Four stations were in 100 ft (30 m) of water, ions, which were at depths of 20 m and 10 m, northeast of

ple Collection

On the last survey day (August 31), water for nutrient and salinity analyses was collected from 30 predetermined locations distributed uniformly throughout the study area (Figure 4-3). At each sampling site, the submersible pump was lowered to within 25 cm of the ocean bottom. Water was pumped for a period of time (approximately 2.5 min) sufficient to ensure at least one hose volume had passed through the hose prior to sample collection. The samples were collected in 500 mL plastic bottles at the outlet of the fluorometer hose. Each volume was then split into nutrient and salinity samples. Nutrient samples were filtered through sub-micron GF/F filters into acid-washed, triple-rinsed 125 mL polyethylene bottles. Sample splits for salinity analysis were poured unfiltered into 60 mL polypropylene bottles. The position, time, depth, and fluorometry readings were recorded for each sample.

4.7 Water Column Profiling

Conductivity-temperature-depth (CTD) casts were made at every second water sampling location within the study area (Figure 4-4) and at every reference sampling station at the same time the water samples were collected (Figure 4-2). Data were collected throughout the entire water column, from the surface to the bottom. The measurements were made with an Ocean Sensors (San Diego, CA) Model OS-100, with an internal data recorder and the following measurement accuracies:

Pressure (decibars)	0.5%	Conductivity (mS/cm)	0.02
Temperature (°C)	0.01	Salinity (PSU) (computed)	0.03

4.8 Sample Analyses

Water samples were analyzed for eight nutrients and salinity by personnel at the University of Hawaii, School of Ocean, Earth Science and Technology Analytical Services Laboratory (Honolulu, HI). Analysis for nitrate-nitrite (NO_3^- + NO_2^-), ortho-phosphate (PO_4^{3-}), ammonium-nitrogen (NH_4^+), and silicon (Si) were performed using a Technicon AAII system with standard procedures modified for high-precision analyses (Technicon Industrial Systems: Industrial methods for water, seawater, and wastewater analysis). Total dissolved nitrogen (TDN) and total dissolved phosphorus (TDP) were analyzed in a similar fashion following ultraviolet digestion. Dissolved organic nitrogen

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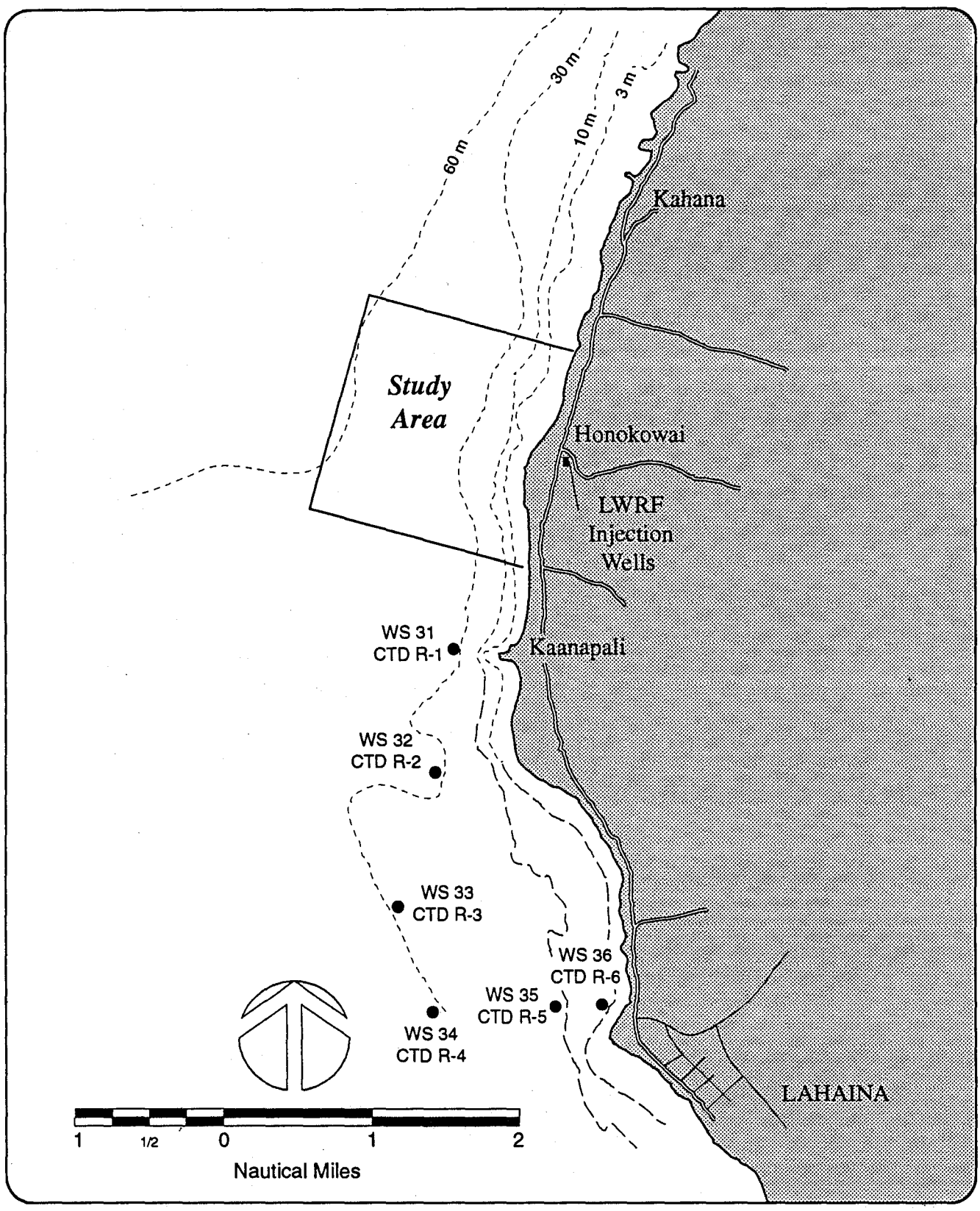

Figure 4-2. Location of water sampling reference stations.

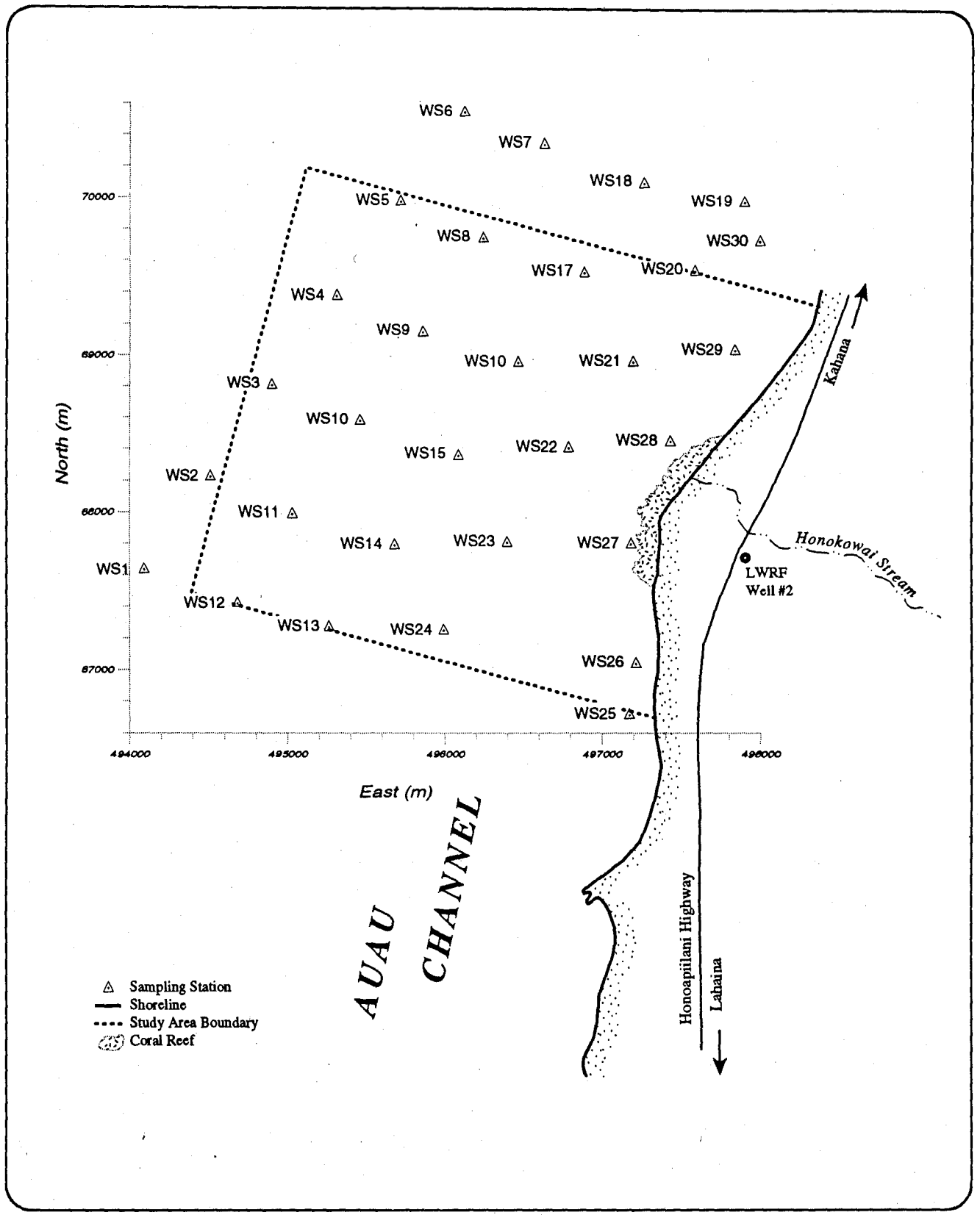

Figure 4-3. Location of water sampling stations for nutrient analyses.

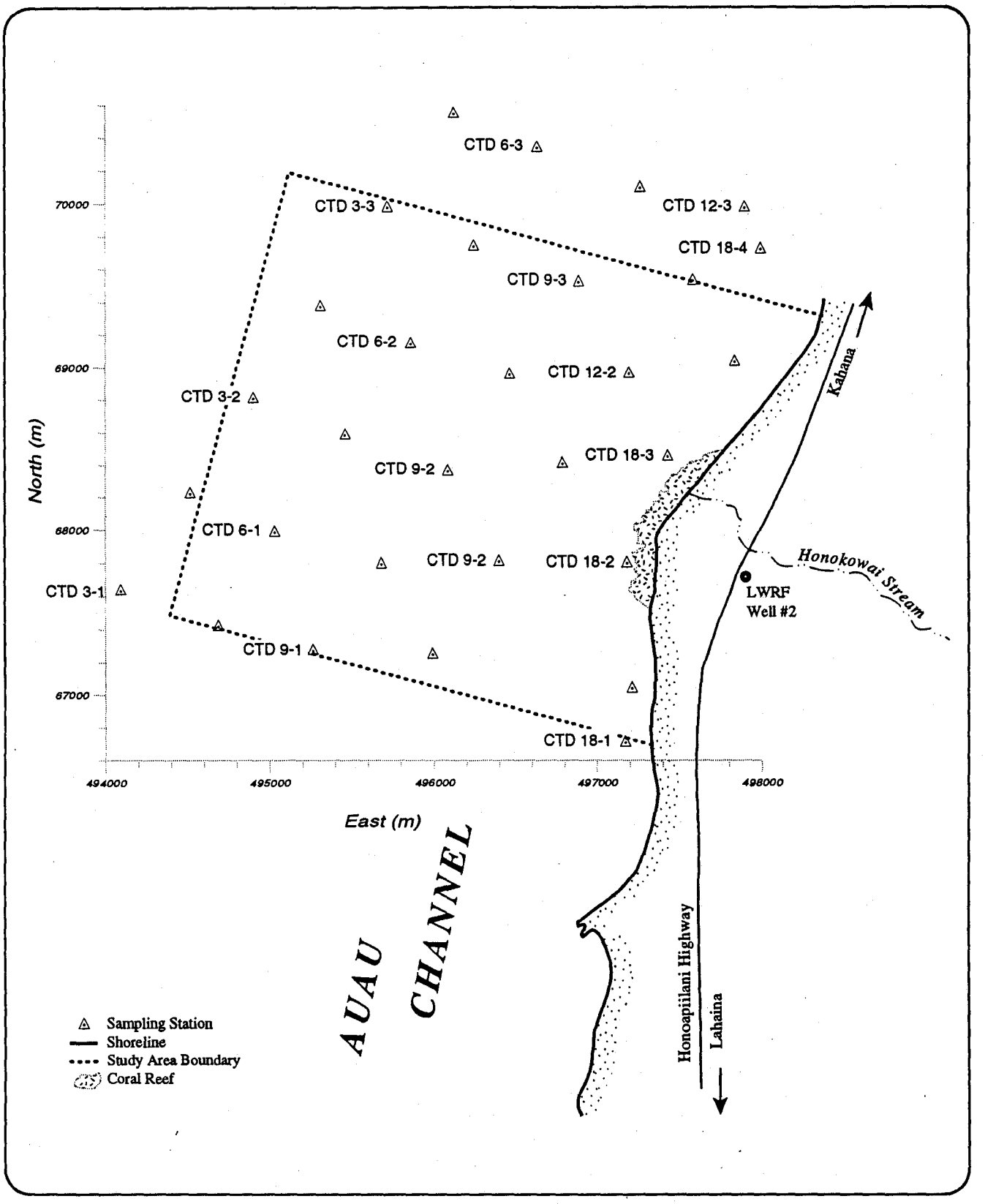

Figure 4-4. Location of water column profile (CTD) stations within the study area.

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(DON) and dissolved organic phosphorus (DOP) were calculated as the difference between total dissolved and dissolved inorganic nitrogen and phosphorus, respectively.

Limits of detection (precision) and accuracy of the nutrient determinations (μM) are as follows:

Parameter	Limit of Detection	Accuracy
PO_4^{3-}	0.01	0.02
NO_3^-	0.03	0.05
NH_4^+	0.03	0.08
TDP	0.02	0.04
TDN	0.2	0.5
Si	0.2	0.5

Salinity of these samples was determined using an AGE laboratory salinometer with a limit of detection of 0.0001‰ and an accuracy of 0.003‰.

4.9 Post-Survey Sampling

Approximately one month after the end of the fluorometric survey, near-bottom water samples were collected from ten locations within the study area (Figure 4-5). These locations were chosen after the initial analysis of the fluorometric survey data had been performed and represented areas of possible elevated readings (Stations S3, S4, S5, S7, S8, S9) or other areas of interest, such as a nearshore area in which bubble seeps and freshwater influxes had been previously reported (Station S1), a station off the mouth of Honokawai Stream (Station S2), and a station at the deepest part of the study area (Station S6).This sampling occurred approximately every week for 2 months, except when prevented by bad weather. The eight sampling dates were:

October 10	November 7
October 15	November 16
October 23	November 28
October 30	December 8

Samples were collected using a conventional water sampling bottle that was lowered by hand to the bottom. The sampling bottle was triggered with a messenger or weight dispatched along the line from the surface. At each site, 250 mL of the sample were collected in polyethylene bottles, labelled, and stored in the dark in a small cooler. The same vessel was used as for the main survey. A single GPS navigation unit (not differential GPS) was used to position the vessel at each of the 10

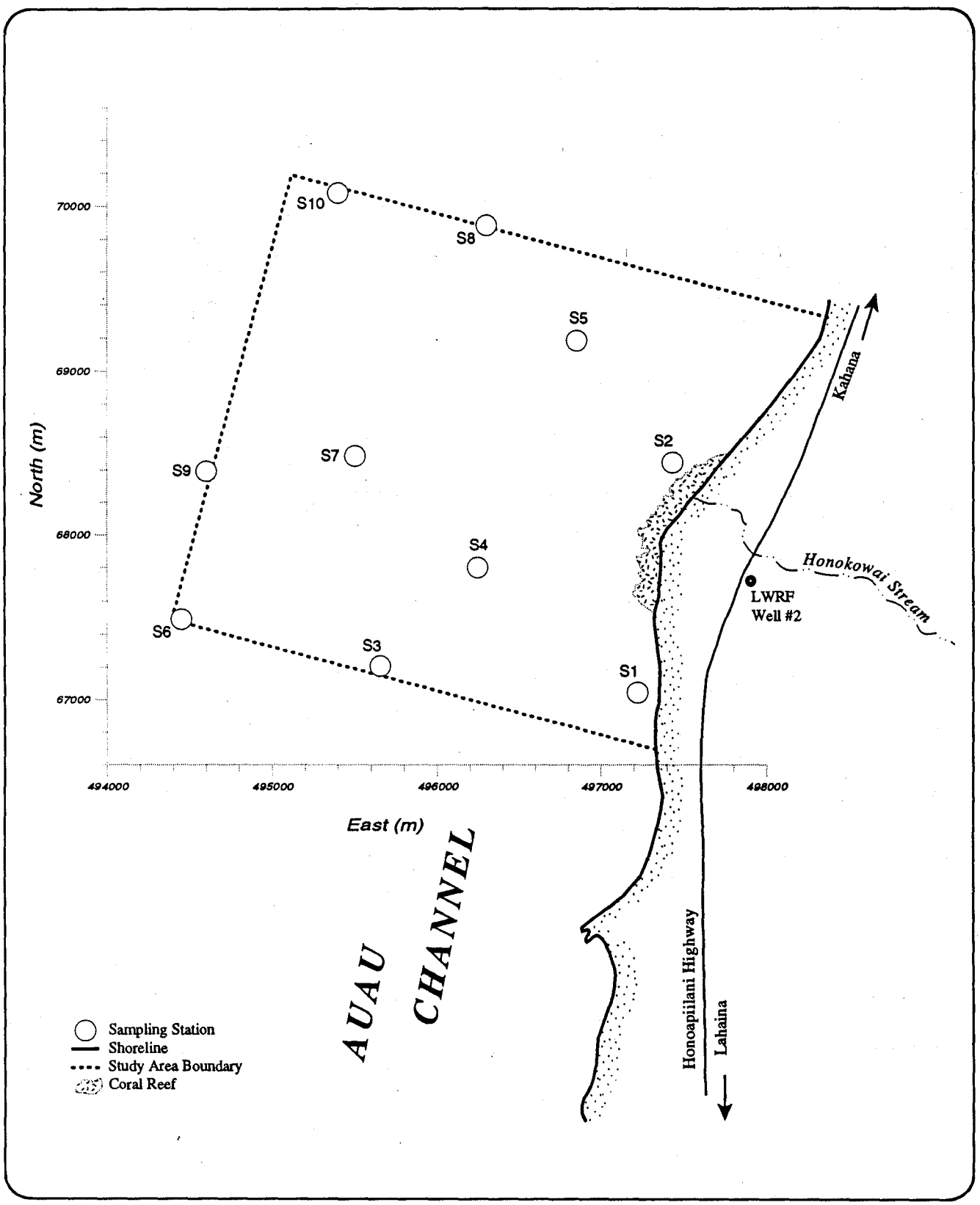

Figure 4-5. Location of post-survey sampling.

locations. The accuracy was estimated to be approximately ± 100 m at the deep sites and considerably better at the nearshore locations, where landmarks could be used to position the vessel somewhat more accurately.

The samples were air freighted to San Francisco where they were analyzed for fluorescence using a Turner Model 112 Digital Filter Fluorometer. The fluorometer was calibrated before each analysis using four standard concentrations of Rhodamine WT dye, ranging from 0.4 to 2.0 ppb. The fluorometer resolution is reported at 0.1 percent of full scale, which is equivalent to 0.002 ppb using these standard solutions. The accuracy is reported to be 1 percent of full scale or 0.02 ppb in this application (Sequoia-Turner Corporation, 1982). The sensitivity, or detection limit, varies with the type of fluorescent tracer analyzed. Under these test conditions with Rhodamine WT, the sensitivity was conservatively estimated to be 0.02 ppb.

5.0 Summary of Findings

5.1 LWRF Operations

During the study period (July and August, 1993), the LWRF treated and discharged an average of 5.6 mgd. Daily influent flow rates varied from a minimum of 4.3 mgd to a maximum of 8.1 mgd. Influent flow data were recorded on a daily basis from a flow meter located at the chlorination plant, except for a period of approximately three weeks in July, during which time the flow meter was not operational. No unusual operating conditions were reported by LWRF personnel during the study period.

Effluent injection rates to Well No. 2 were recorded three times a day from a flow meter at the splitter box between Injection Wells No. 1 and No. 2, the same location in which the tracer was added to the effluent. The average daily flow for the 2-month period was 3.0 mgd, with a maximum flow of 3.7 mgd and a minimum of 2.4 mgd. A graph showing the total effluent volume treated and effluent flow through Injection Well No. 2 is shown in Figure 5-1.

5.2 Study Area Bathymetry

Bathymetric contours were constructed from the depth data recorded during the main survey. Contours were computed after editing the depths recorded at each of the near-bottom sampling points (Figure 5-2). Heave and tidal corrections were not applied to the values and the depths were estimated to be accurate to ±0.5 m.

Isobaths remain parallel to the shore throughout the study area except at the deep southwest corner. The major bathymetric feature of the study area is a broad ledge or bench, at 35 m to 45 m in depth, between 1,200 m and 1,600 m wide and approximately 1,000 m offshore. Closer to shore, the water remains shallow across the coral on Honokawai Point and to the north past the mouth of Honokawai Stream. To the south, the inshore water deepens more quickly.

Moving away from the shore, the bottom drops off relatively quickly from 10 m to 35 m in depth. This occurs more quickly in the southern portion of the study area. The depth increases more rapidly at the southwestern corner of the study area, to over 70 m. At the northwestern corner of the area, the depth increases also, but more slowly, to less than 60 m. At the southern edge of the study area, a depression of 5 m or more is evident running north-south and extending about 700 m into the study area. However, from the data collected, it cannot be determined how far it extends toward the south.

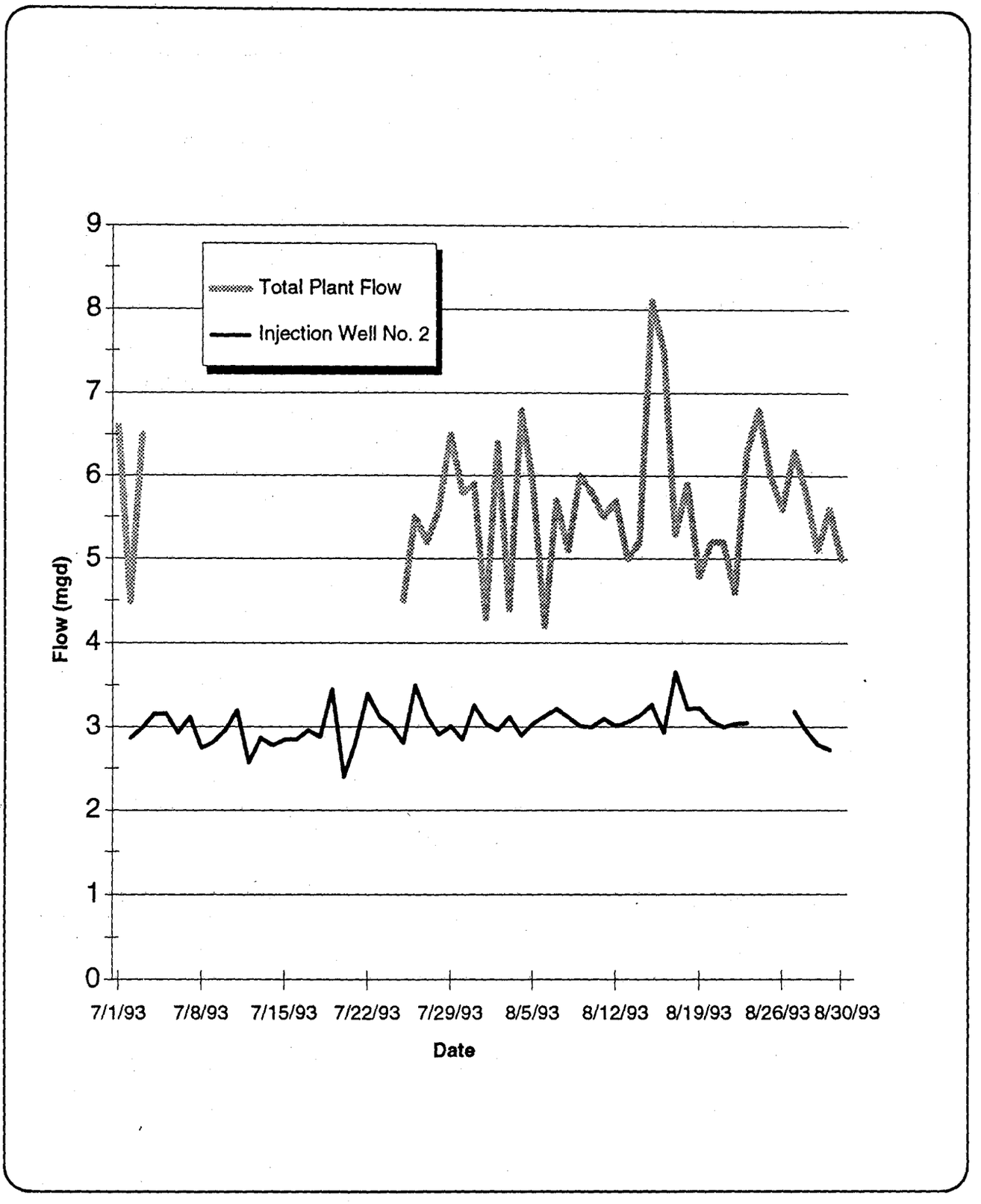

Figure 5-1. LWRF total daily flow and Injection Well No. 2 daily flow.

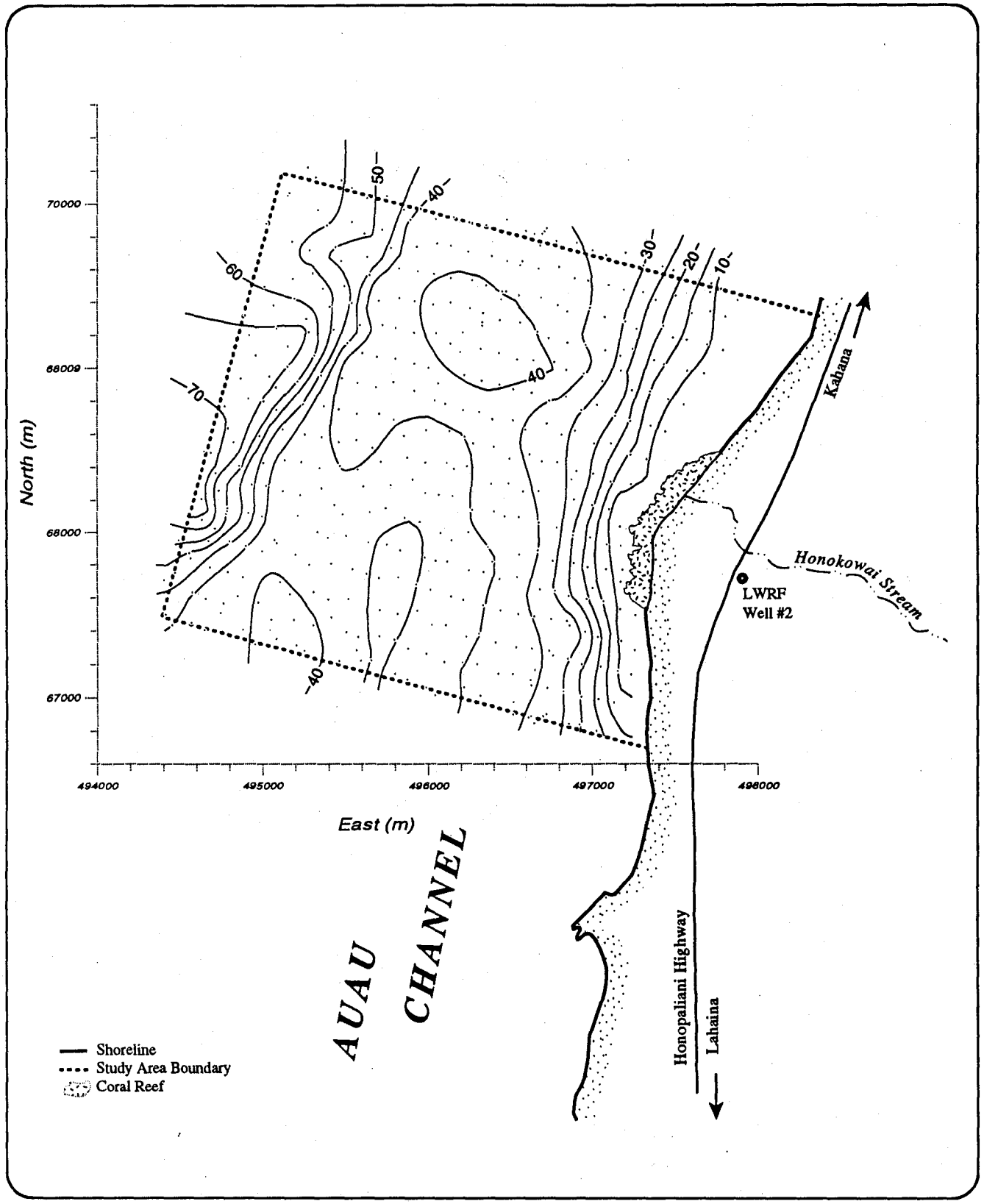

Figure 5-2. Bathymetry of the study area.

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A three-dimensional projection of the recorded bathymetry is presented in Figure 5-3. The vertical exaggeration of this projection is 30:1.

5.3 Fluorometric Survey Results

The main survey was performed over two 4-day periods, with a break of one day between each half. Every second transect (Line 1 to Line 17) was run in the first half, and the remaining transects, Line 1A to Line 18A, were surveyed in the second part. Adverse weather conditions prevented the lines from being run in numerical order during either half of the survey. The transects were surveyed in the following order and on the following days:

Date	Line No.
August 22	15, 12, 11, 10, 16
August 23	9, 8, 14
August 24	5, 6, 4, 17
August 25	7, 3, 2, 1, 13
August 27	5A, 4A, 3A, 2A, 1A, 6A
August 28	7A, 8A, 9A, 10A
August 29	11A, 8A*, 12A, 13A, 16A
August 30	14A, 15A, 17A, 5A*, 8A*, 15*,18A

* indicates resurvey of sections of lines to confirm elevated readings from initial survey of the same lines

The fluorometry data analysis was performed in three steps:

- all the 3-sec averaged data were plotted as separate line graphs of fluorescence versus time and temperature versus time (after instrument calibration corrections had been applied)

- a statistical analysis of the daily data collected was performed to distinguish signals from background and instrumental noise. Mean values and 95-percent confidence limits were calculated and scattergrams of concentrations were plotted for each of the eight survey days

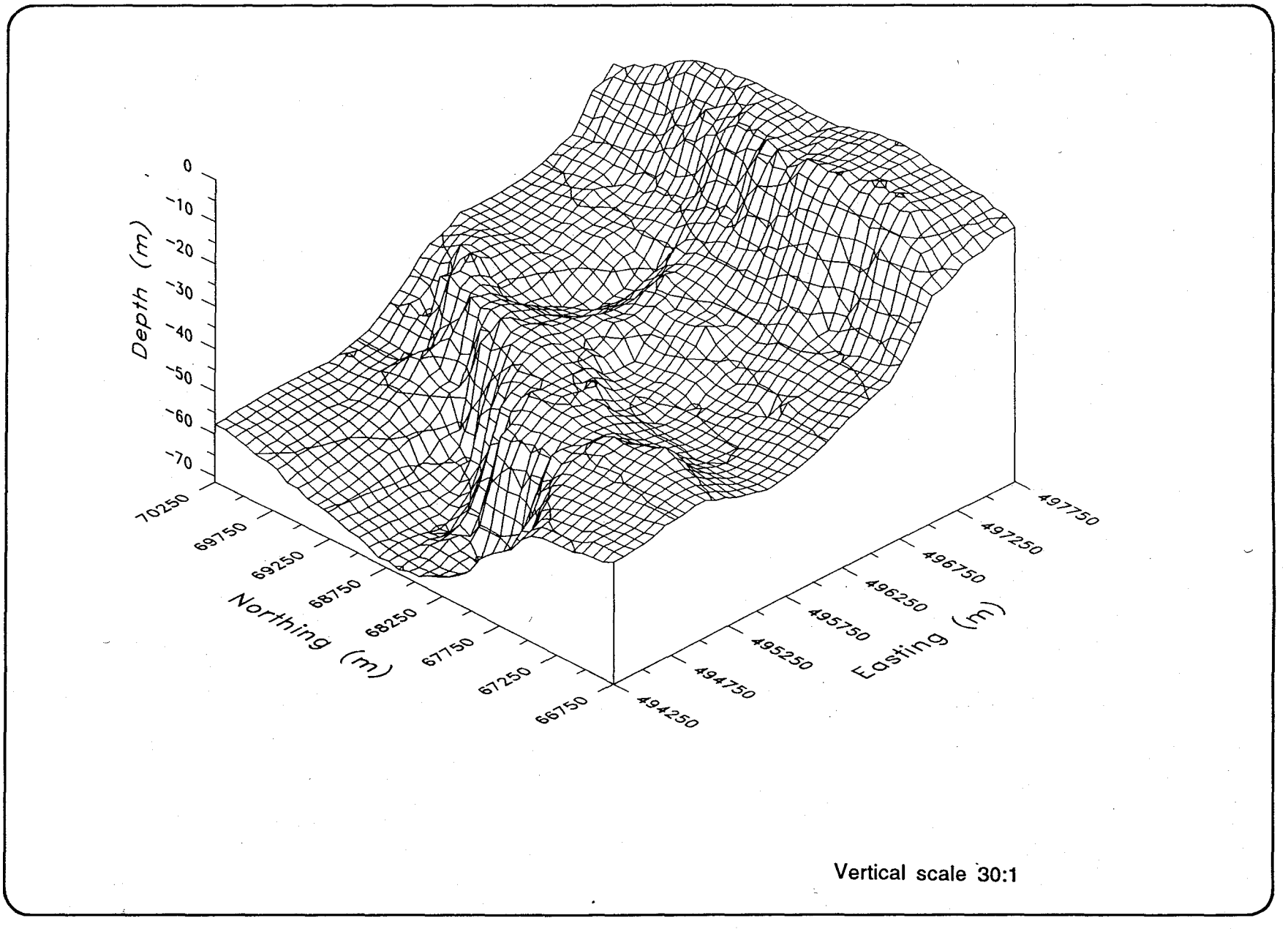

Figure 5-3. Three-dimensional plot of the study area.

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- contour charts for near-bottom fluorescence were compiled and plotted from the 3-sec averaged data collected from each half of the survey to be used as tools in the analysis of spacial patterns of the signals and to present the final interpretation of the data.

5.3.1 Fluorescence and Temperature Graphs

Graphs of fluorometry data, as concentrations reported relative to a calibration standard of 1.00 ppb of Rhodamine WT, and of temperature (°C), are presented in Appendix A in order of transect number. The data are raw 3-sec averaged values, as recorded by the internal data logger of the fluorometer. Corrections for the approximate 2 min travel time between the pump and the instrument have not been applied, nor are the data corrected for background fluorescence. Instantaneous fluorometer readings were recorded separately every 15 sec onto the navigation computer hard drive. After an initial analysis using the 15-sec instantaneous data, the 3-sec averaged data were chosen for a more detailed analysis because the data were recorded more frequently and the data were more consistent than the instantaneous data. The data were considered a more accurate representation of conditions during the study because, for a typical sampling location, the near-bottom water was pumped through the fluorometer for approximately 1.5 min and during this period only six 15-sec values were recorded compared to thirty 3-sec values.

Three major characteristics of the data could be discerned from the line graphs:

- oscillations in temperature readings occurred consistently throughout both halves of the survey and related small variations of concentration were evident on some lines

- many distinct peaks of fluorescence at two to three times background values were recorded when the pump was near the bottom during the first half of the survey

- variations in fluorescence were much smaller and were close to the detection limit of the instrument during the second half of the survey when two extra filters were installed in the water intake line.

Temperatures were seen to vary consistently by about 1 °C along each transect. The lower readings correspond to near-bottom water temperatures and the higher readings to the surface water temperatures. Corresponding small-scale oscillations, in the opposite direction, were discernible in the fluorometer readings for most transects. These oscillations were generally at or below the sensitivity limit of the instrument. They were through to be the result of backscattering by very fine particles

near the seafloor, or inaccuracies in the temperature compensation circuitry, or a combination of both. These effects were more pronounced because the background signal was very low and the fluorometer is operating at the low end of its sensitivity range (S. Mokelke, January 17, 1994, personal communication).

The majority of high values were recorded during the first four days of the survey. These elevated signals were associated with near-bottom water samples, and during the initial days of the survey, they were thought to be real signals. However, sand particles were detected in the water at the fluorometer outlet. It was then realized that, as the weight and pump moved across the seafloor, sand and finer particles may have been disturbed and sucked into the intake hose. As the particles passed through the flow-cell of the fluorometer, light was refracted from the particles at different frequencies, creating false readings. To verify this possible source of interference, background near-bottom samples were measured at a shallow site remote from the study area. Similar elevated readings were recorded as the pump and weight were observed moving across the seafloor. To compensate for this interference for the second half of the survey two extra filters were installed in the hose line to trap suspended particulates before the water entered the fluorometer measuring cell.

As further verification of interference, several discrete water samples were collected along different transects at the same time the fluorometer was recording high readings. These discrete samples, all of which contained visible particles, were analyzed later the same day using the fluorometer set up in a discrete sample measuring mode. No elevated readings were recorded if the samples were not stirred before being poured into the measuring cuvette (Table 5-1). The same sample, if stirred briskly before pouring into the fluorometer cuvette, was measured at a higher concentration than the unstirred sample, indicating that the higher reading was a result of backscattering of the light signal by the particles in suspension. Because of the presence of the particles and the variations in readings, the elevated flow-through readings recorded in the first 4 days of the study were considered to be the result of light backscattering. If true signals were present, they would have been masked by this interference.

Post-survey analysis of all the data sets supported the presence of interference in the samples collected during the first half of the survey. In general, elevated readings were present only along every second transect, and did not occur along adjacent transect lines. An example of this can be seen from the following figures. Figure 5-4 is a line graph of fluorescence of the unfiltered water versus time recorded on transect Line 4. Elevated signals, due to suspended particulates in the sample, are obvious at nine near-bottom stations. Figure 5-5 shows the equivalent graphs for the adjacent Line 4A and Line 5A (100 m to the east and west of Line 4, respectively), in which the water passed

TABLE 5-1. DISCRETE SAMPLING CONCENTRATIONS

Transect No.	Date	Sampling Time	Concentration (ppb) Flow-through	Discrete sample
4	8/24/93	11:20:00	0.232	0.027
4	8/24/93	11:54:20	0.27	0.033
5	8/24/93	7:38:55	0.115	0.042
6	8/24/93	9:11:11	0.117	0.036
6	8/24/93	9:37:40	0.15	0.024
6	8/24/93	9:41:50	0.165	0.023
6	8/24/93	10:22:50	0.137	0.026
2	8/25/93	10:50:33	0.12	0.021
3	8/25/93	9:09:08	0.14	0.018
3	8/25/93	9:28:20	0.135	0.019
3	8/25/93	9:31:25	0.122	0.018
7	8/25/93	7:14:10	0.117	0.019
1A	8/27/93	11:46:10	0.056	0.018
5A	8/27/93	8:17:10	0.057	0.017
6A	8/27/93	11:11:25	0.058	0.016
7A	8/28/93	8:43:20	0.065	0.016
8A	8/28/93	9:25:00	0.08	0.017
16A	8/29/93	13:33:00	0.065	0.024
15R	8/30/93	11:54:10	0.05	0.019

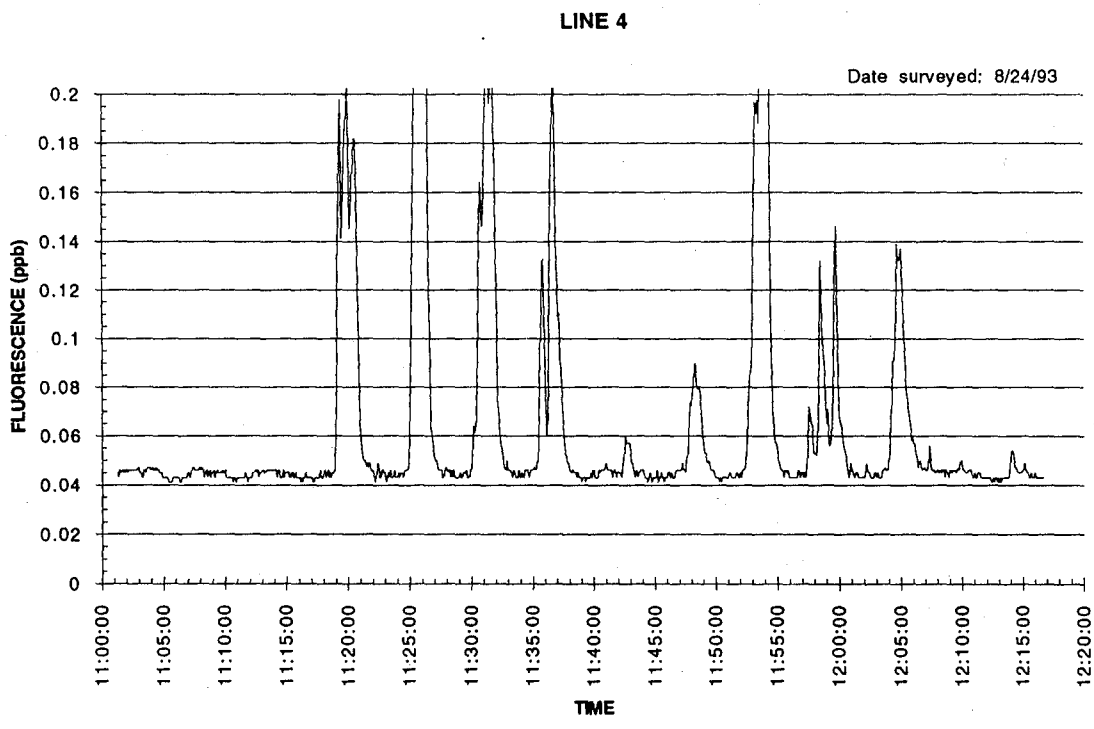

Figure 5-4. Fluorescence readings recorded on Line 4 with one filter in-line.

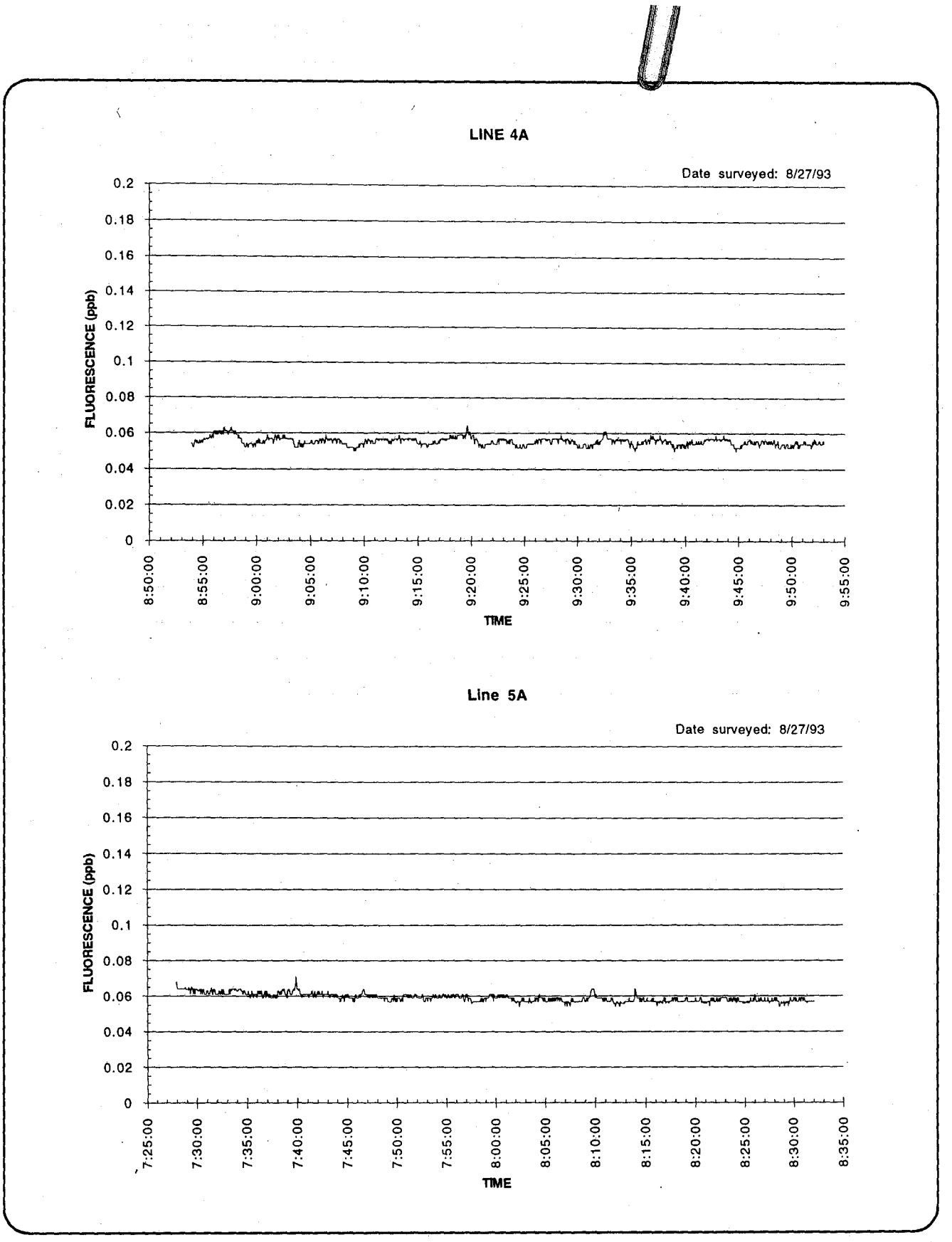

Figure 5-5. Fluorescence readings on lines adjacent to Line 4, using three in-line filters.

through two additional filters before reaching the fluorometer. These plots show only a small variation of concentration of 0.05 - 0.07 ppb. This alternating pattern of high readings and near background readings along adjacent transects was repeated along other transects, which supports the concept that the elevated readings were a result of an interference mechanism, and are not representative of a naturally occurring effluent discharge pattern.

5.3.2 Statistical Analysis

Overall, not considering signals resulting from interference from suspended particulates, the data are characterized by a small signal-to-noise ratio and the variations in readings for the majority of the data are small and close to the limits of deductibility of the instrument. A simple statistical analysis of the data was performed to identify possible signals within the background variations. The mean and standard deviation were calculated for the 3-sec averaged data collected each day (Table 5-2). These data were plotted as scattergrams of daily observations versus concentration, and the mean value and 95-percent confidence limits, represented by 1.65 standard deviations were plotted also (Appendix B). Points falling outside the upper confidence limit were identified for further inspection, after the data were contoured, to determine the extent of continuity of elevated values across adjacent transects.

5.3.3 Fluorometric Contours

The third part of the data analysis was to identify possible spatial patterns of variations of concentrations in the near-bottom waters. Contour charts of near-bottom fluorescence were prepared from the 3-sec averaged data and the navigation records of the vessel's position when the pump and first reached the bottom. Fluorescence and position readings were corrected for the time delay of the water travelling through the intake hose. After these corrections were applied, the concentration values corresponded to the horizontal grid position at which they were recorded.

Where sections of transects had been resurveyed to verify areas of elevated concentrations, the highest readings were plotted initially and the subsequent resurvey data, which were lower in all cases, were not used in the contour plots. This was done to ensure that no valid elevated readings were discarded.

Because of the interference encountered in the first half of the survey and because each half of the survey covered the entire study area, the data collected from each half were contoured separately. This approach was used as a further step to confirm whether the peak concentrations recorded during the first half were valid signals or the result of interference. If the signals were indeed valid, then the

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TABLE 5-2. DAILY STATISTICS OF FLUOROMETRIC DATA

Date	Mean	Std. Dev	Minimum	Maximum	Range	Count
Single in-line filter. Transects 1 through 17						
8/22/93	0.053	0.014	0.043	0.28	0.237	5517
8/23/93	0.051	0.0074	0.043	0.117	0.074	4776
8/24/93	0.06	0.032	0.041	0.405	0.364	3107
8/25/93	0.052	0.011	0.039	0.115	0.076	5554
Three in-line filters. Transects 1A through 18A						
8/27/93	0.057	0.0045	0.048	0.078	0.03	6132
8/28/93	0.051	0.0089	0.041	0.082	0.041	6866
8/29/93	0.05	0.0034	0.045	0.086	0.041	6358
8/30/93	0.052	0.0063	0.045	0.187	0.142	4052

two plots of contours of equal concentration should exhibit similar spatial patterns. However, this was not the case.

Initially, near-bottom concentration values were plotted relative to the grid locations (easting, northing) at which the values were recorded. This was done for each half of the survey (Figures 5-6 and 5-7). Although these plots of spot values show the complete data sets, they are difficult to interpret. So, the data set from each half of the survey was then computer-contoured to produce plots of lines of equal concentration (Figures 5-8 and 5-9). For each chart, the corresponding positions of the data points used for the contouring were plotted as small dots. Each dot corresponds to the concentration value shown on the previous figures (Figures 5-6 and 5-7).

These 0.01-ppb contour plots show distinct concentration patterns. The apparent southwest-northeast trend in the concentration contours is thought to be an artifact of the data collection procedure because each transect was run in the same northeasterly direction.

The plot of the first half of the data (Figure 5-8) exhibits high concentrations in the western section of the study area, most corresponding to data collected along Line 4 and Line 6. A single high value is evident at the beginning of Line 2 along the western edge of the area, and another is evident in the southeast corner, at the beginning of Line 17. These characteristics and the overall structure of the pattern can be seen more clearly in Figure 5-10, in which only contours greater than the background value of 0.06 ppb are plotted.

Figure 5-9 shows the contours generated from the data collected in the second half of the survey, when the water passed through three filters before reaching the fluorometer. This plot is very different from Figure 5-8. No elevated concentrations were present in the northwest section of the study area and the concentrations overall were much lower. The only exception was a single high value in the southeast corner. Again, these characteristics can be seen more clearly in Figure 5-11, in which only contours greater than 0.06 ppb are plotted. The considerable difference between the plots from each half of the survey are more obvious when Figures 5-10 and 5-11 are compared.

5.3.4 Data Interpretation

The lack of continuity across transects for the high concentrations recorded in the first half of the survey suggest that the observed contour patterns did not result from the presence of tracer, but are caused by interference to the fluorescence signal. In only one instance are high concentrations observed across adjacent lines. This occurs at the southeastern corner of the study area, where maximum values of 0.18 ppb were recorded at the beginning of Line 17A and at the beginning of

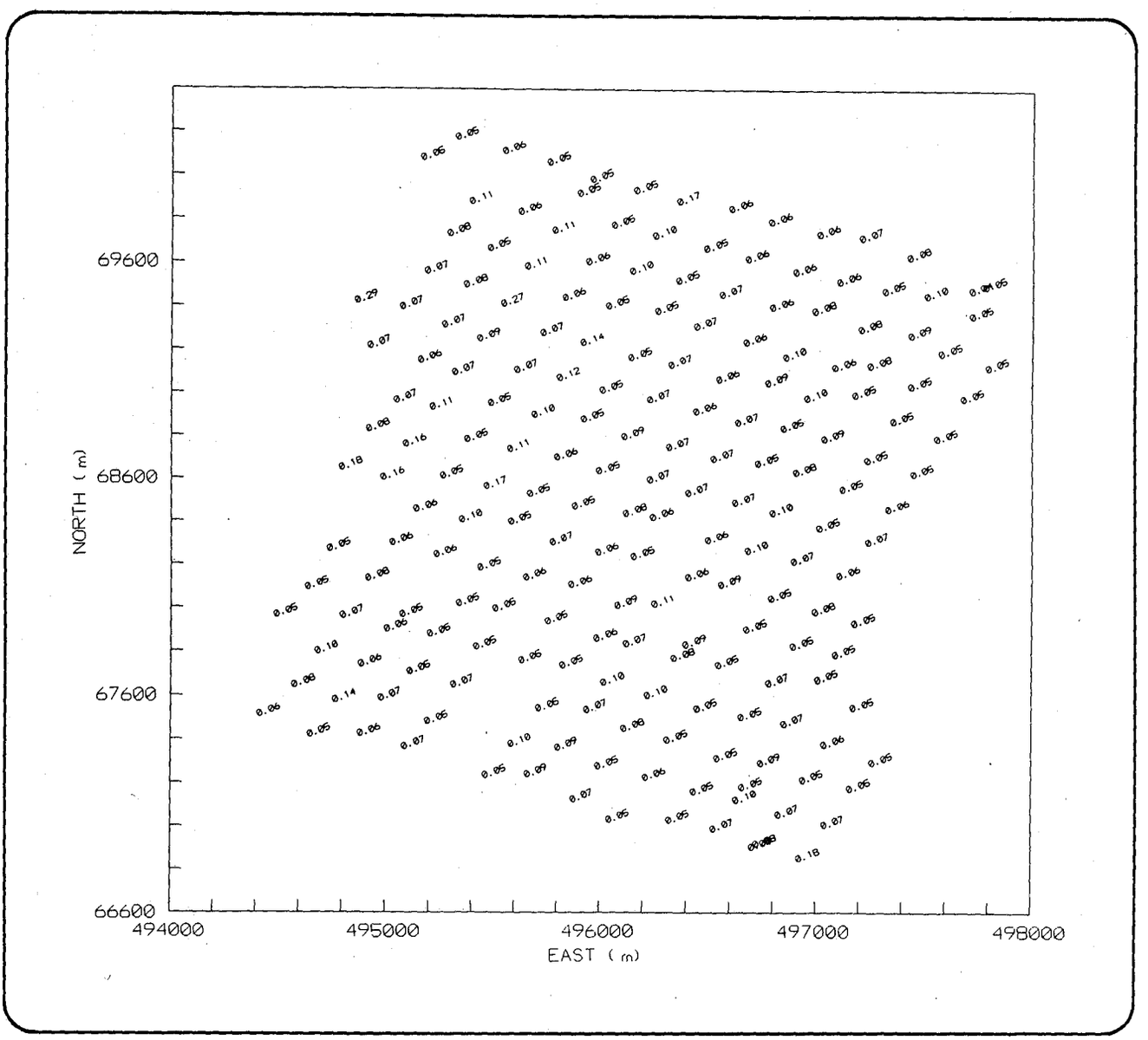

Figure 5-6. Concentration (ppb) versus grid location for unfiltered samples.

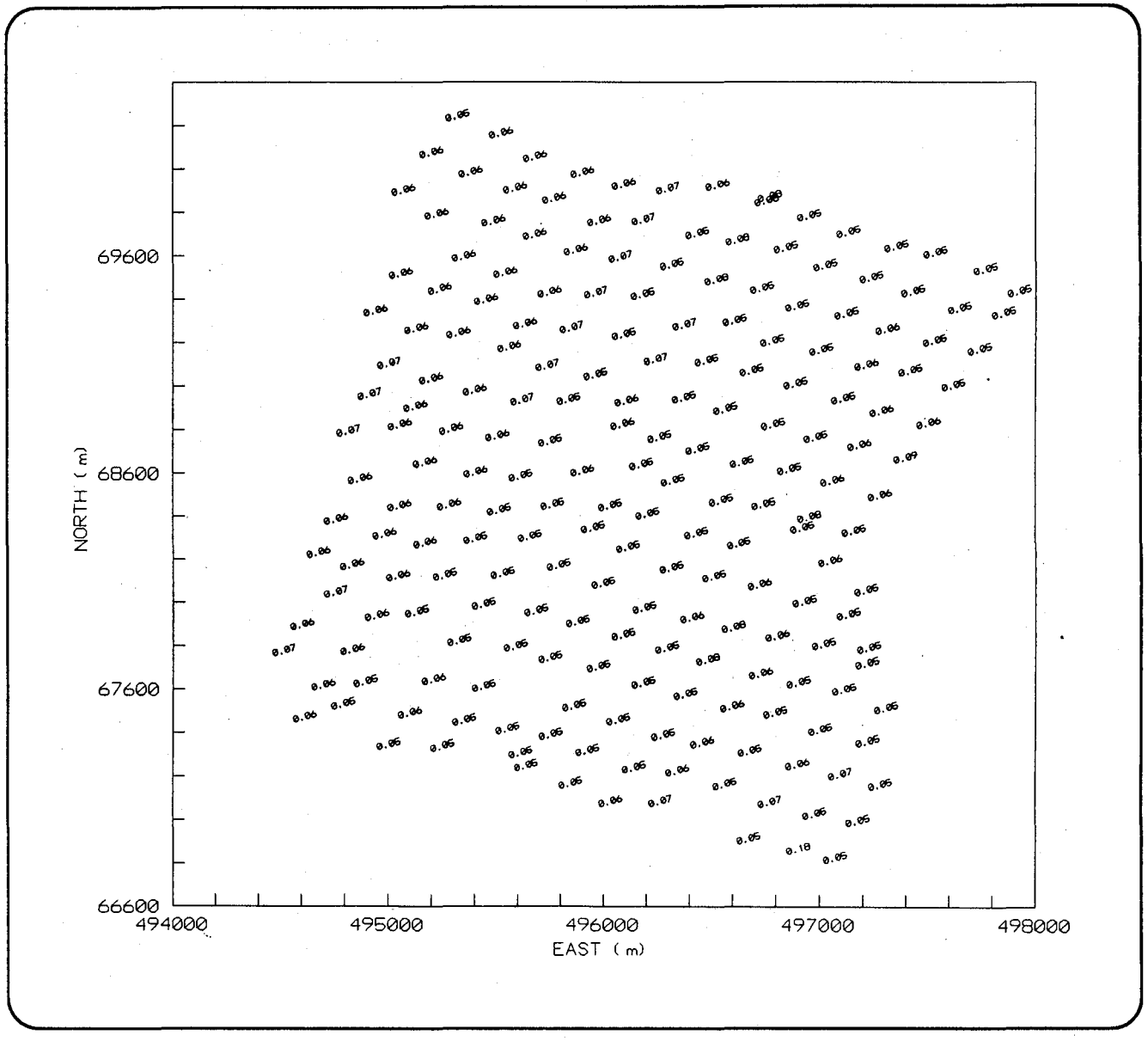

Figure 5-7. Concentration (ppb) versus grid location for filtered samples.

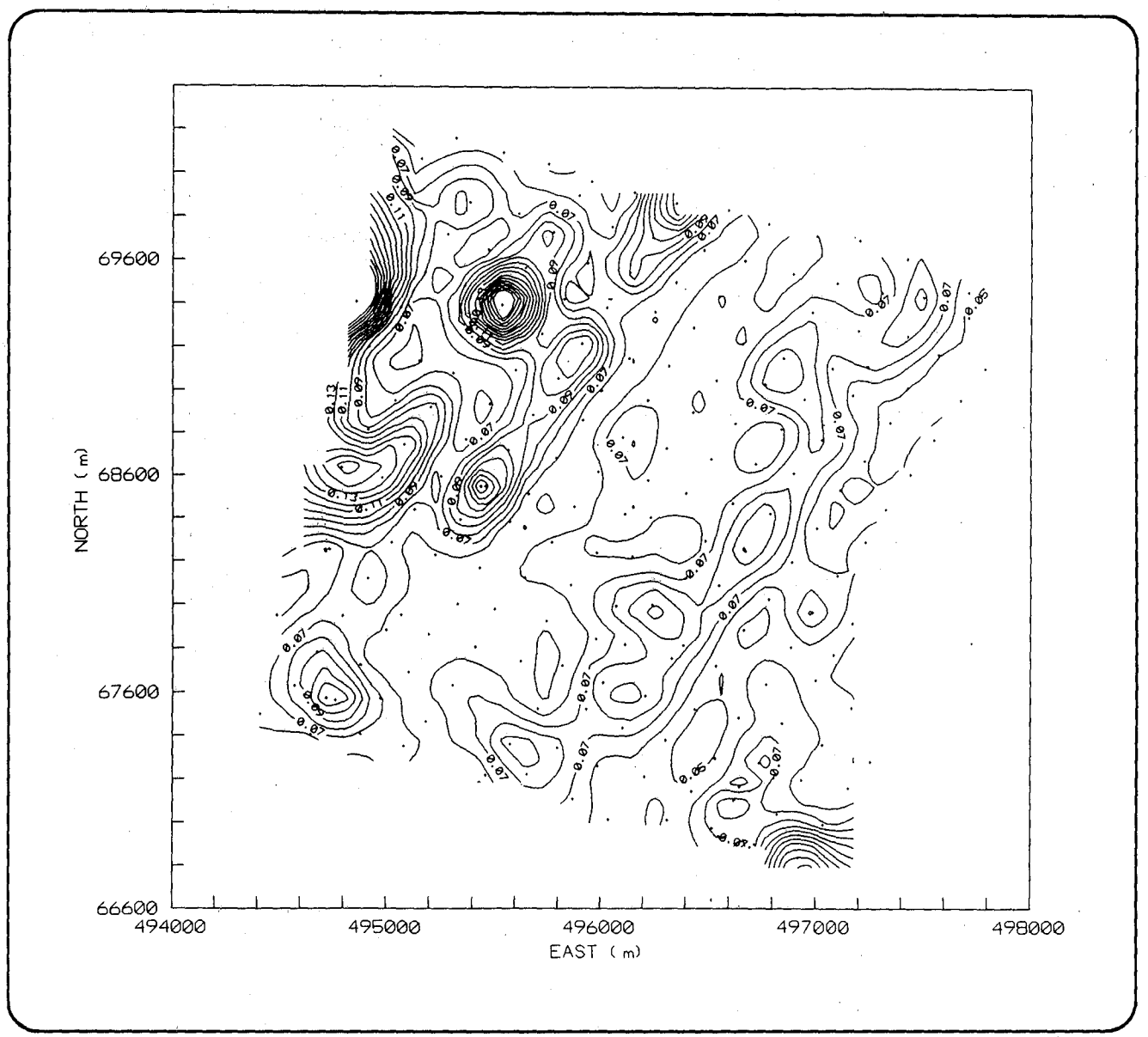

Figure 5-8. Concentration contours (ppb) for unfiltered samples.

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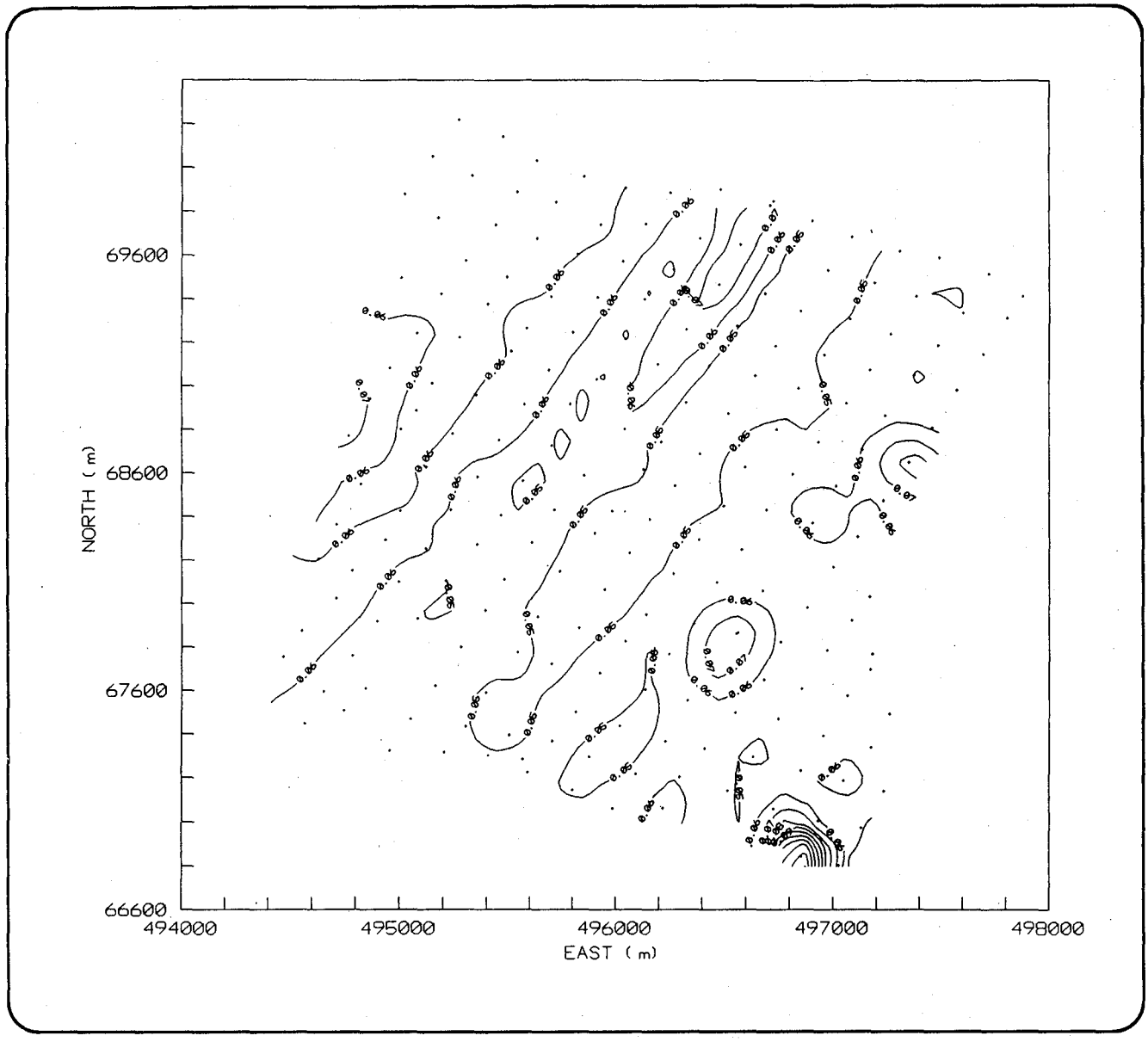

Figure 5-9. Concentration contours (ppb) for filtered samples.

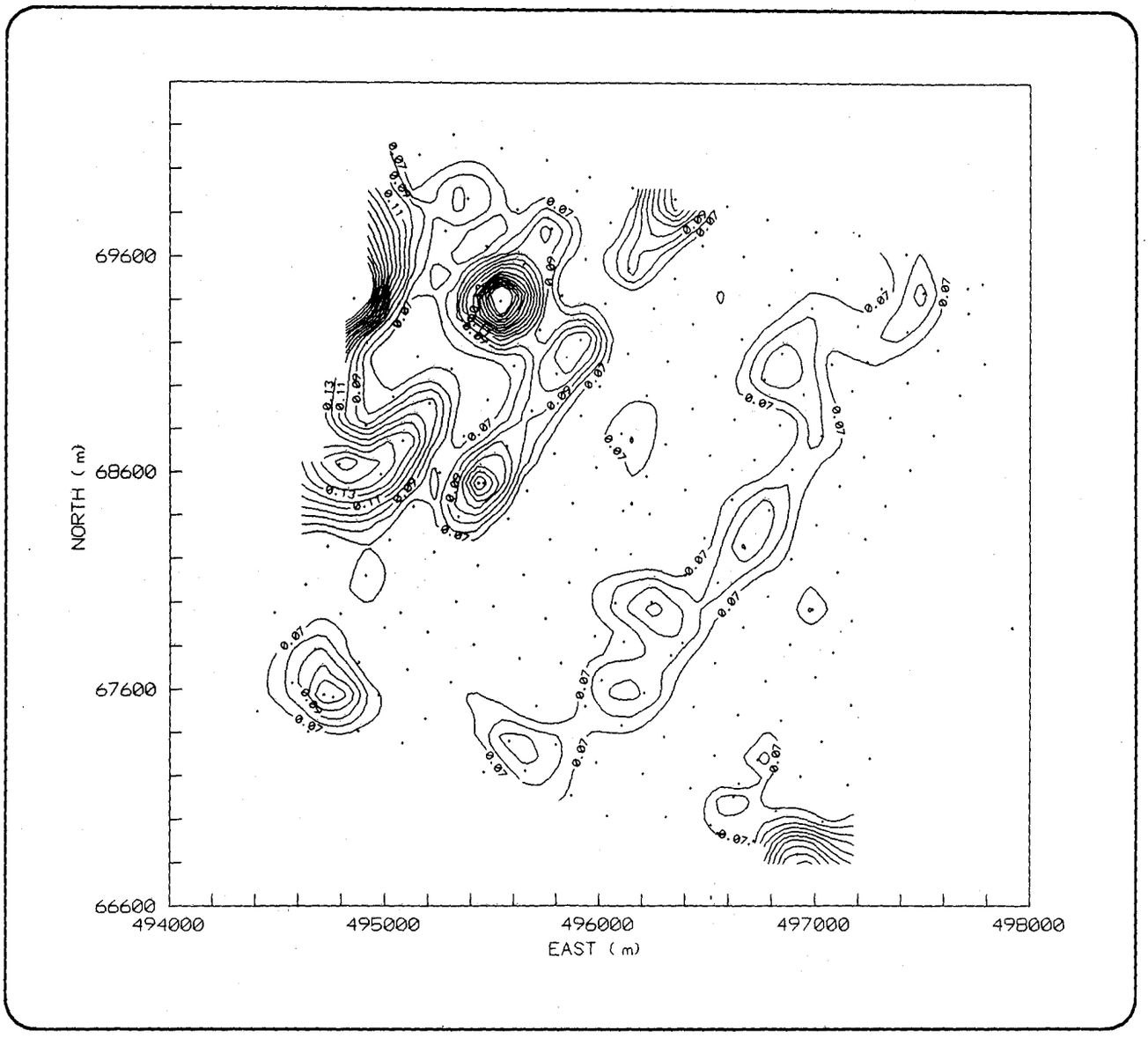

Figure 5-10. Concentration contours greater than 0.06 ppb for unfiltered samples.

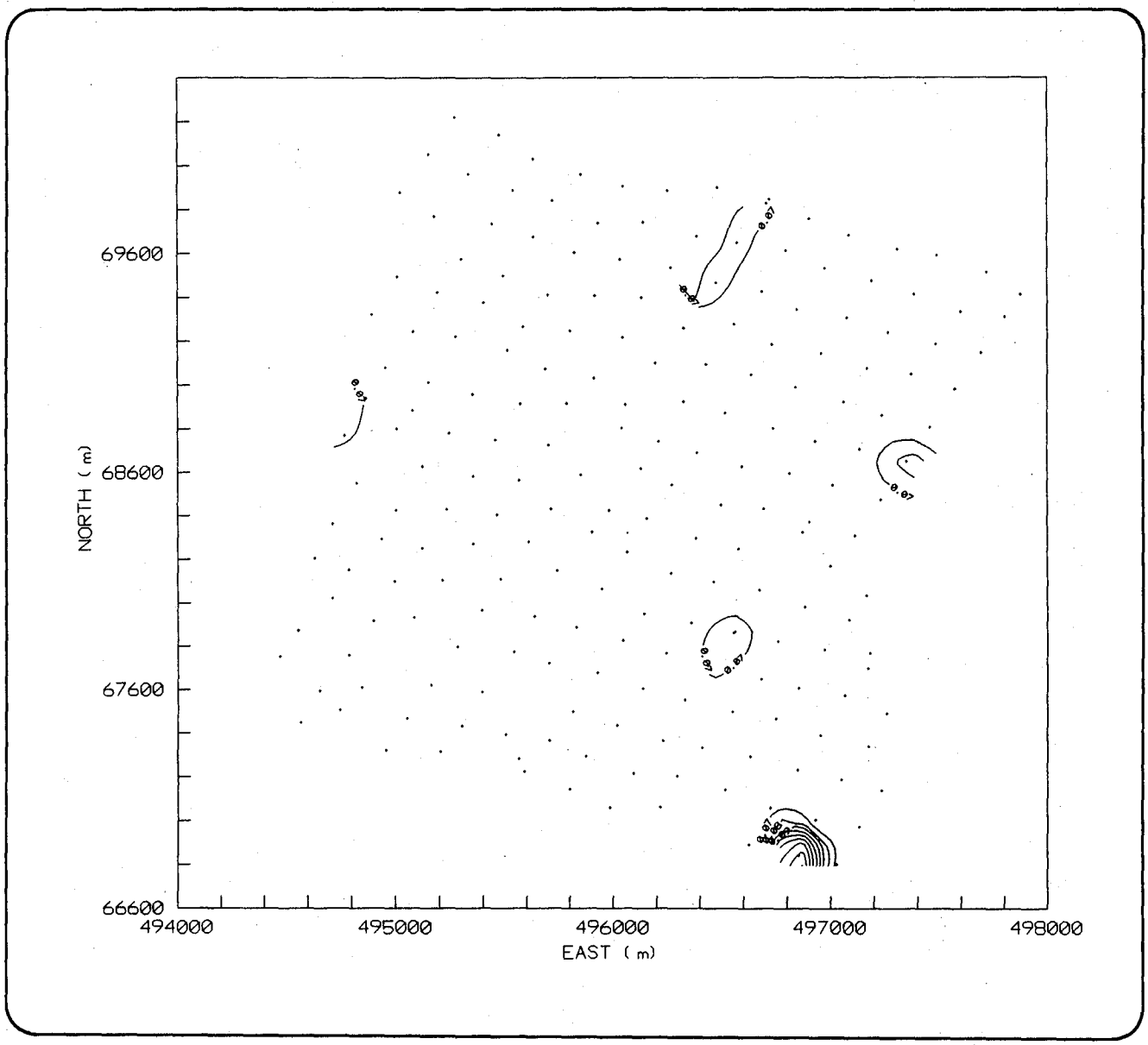

Figure 5-11. Concentration contours greater than 0.06 ppb for filtered samples.

Line 17. Inspection of the concentration point plots (Figures 5-6 and 5-7) show near background concentrations adjacent to both high values. In both instances, elevated readings were recorded from near-bottom water and for durations of about 1.5 min, which is the approximate time the pump was near or on the bottom. However, elevated signals were not recorded at other adjacent locations, 200 m to the north or east, or 100 m to the west. Both of the readings occurred at the beginning of transects, and no data was collected south of either location.

From Figure 5-11, four other areas of concentrations above background are evident. On the western edge of the study area are two points at the beginning of Line 3A with values of 0.75 and 0.72 ppb. The differences between these values and the background are close to the limit of sensitivity of the instrument. Adjacent data from the first half of the survey is probably masked by interference and cannot be used to support the existence of elevated concentrations in this area.

At the northern edge of the study area, five points between 0.075 and 0.082 ppb were recorded along Line 8A (see Appendix A). These signals exhibited different characteristics than other peaks measured during the survey. Usually, the minimum values remained constant at background levels and a large variation in concentration occurred only in the near-bottom water. In this case, the minimum concentration also increased approximately 0.02 ppb above background and the variation between maximum and minimum values did not vary markedly from other background transect data. This suggests that if increased fluorescence was detected, it was detected throughout the water column, and not just in the near-bottom waters.

This section of Line 8A was resurveyed twice, on 8/29/93 and on 8/30/93, in an attempt to verify the initial readings. Both times no concentrations above background levels were recorded. The data from the resurveys are not incorporated in the data for Figure 5-11. The lack of repeatability of elevated readings suggest that the original readings were a result of an unknown interference mechanism and elevated concentration did not exist; or if a true signal was present, it represented a narrow plume of slightly elevated concentration which varied with location or time. That is, during the periods of the resurveys, the concentration had diminished or the location of the plume had shifted to the east or west. However, because the current was observed to flow consistently in a northerly direction, it was unlikely a plume would move that far. Temporal variations in the rate of flow of a plume cannot be explained, either. Injection rates at the wells were relatively constant, and flow paths through the ground water system are also thought to be consistent.

The third area of elevated readings occurred along the eastern boundary of the study area, along transect 14A. Inspection of the line graph in Appendix A shows a single sharp peak (to 0.94 ppb) of

duration of approximately 30 sec. Adjacent records from Line 13 and Line 14 indicate background levels only. If this is a valid reading, the elevated concentrations remain close to the seafloor and concentrations fall to background levels rapidly, estimated to be within 10 m of the detection point.

The fourth area of elevated readings is marked by the small 0.07 ppb contour to the south of the center of the study area. This occurred on Line 13A where three readings greater than 0.07 ppb were recorded (Appendix A). Data from the adjacent transect to the west, Line 12, appears to be masked by backscattering interference and data from the adjacent Line 13, to the east, shows a single elevated peak but it is further north along the line. If these readings on Line 13A represent true elevated concentrations, the concentration falls to background levels within 100 m to the east and west and varies for 1,000 m north along the line from 0.08 ppb to background levels.

The data and the field logs were inspected carefully for each of the locations and times discussed and no obvious problems that would result in interference or false readings were identified. However, interference, or false readings from unknown sources or from instrumental variations cannot be completely ruled out when the signals are of similar magnitude to the background variation and the instrument detection limit, and four of the five possible valid signals are close to the limit of sensitivity of the instrument. The fifth signal, at the southeast corner of the study area, was detected on adjacent lines on two separate days, but in each case, at only one location. Of all the elevated concentrations recorded, this location was the most likely to be a valid detection of tracer. However, without further data, especially to the south of the location, it cannot be positively stated that tracer was present at the time and location of sampling.

5.3.5 Dilution Calculations

The tracer was added to the effluent injected into Well No. 2 at a daily average volume of 1.5 L of active dye. The average effective tracer concentration at the wellhead was between a minimum of 71 ppb, compared to the average total daily flow of the LWRF of 5.6 mgd (21.2×10^6 L/day), and a maximum of 132 ppb, using only the average effluent flow at Well No. 2 of 3.0 mgd (11.4×10^6 L/day). The possible loss of active tracer due to uncontrolled mechanisms, such as oxidation and adsorption were estimated to be not more than 10 percent.

The field resolution of the fluorometer was estimated to be approximately 0.02 ppb. The background concentrations within and beyond the study area varied from 0.04 to 0.06 ppb. Based on these values, for the tracer to be present in the study area at undetectable limits, dilutions of at least 3,200 ([71 ppb x 0.9]/0.02 ppb) would be required, assuming the effluent from all four wells is

completely mixed in the ground water. Dilutions of 5,900 ([132 ppb x 0.9]/0.02 ppb) would be necessary if the effluent from Well No. 2 did not mix with the effluent from the other wells after injection.

Along Line 13A where concentrations of 0.08 ppb were recorded (0.02 ppb above background), the estimated dilution of the effluent and tracer, if present, was close to the maximum detectable dilutions of 3,200 to 5,900. Along Line 14A, at the location of the brief high reading of 0.09 ppb, the minimum dilutions required to achieve the recorded value were 2,100 to 3,900. At the southeast corner of the study area, where two separate values of 0.18 ppb (0.13 ppb above background) were recorded, effluent dilutions would be between 500 and 900 times the wellhead concentrations, again depending on the mixing characteristics of the effluent after injection. However, these dilutions would have to exceed the maximum detectable values of 3,200 to 5,900 within 100 m to reach the observed background concentrations at the surrounding sampling points.

In summary, five possible areas of elevated fluorescence were identified from the triple-filtered samples collected during the second half of the survey. At three of these areas, elevated concentrations were 0.02 to 0.03 ppb above background values. This variation was similar to the background variation reported over the duration of the survey, and similar to the field detection limit of the instrument. The fourth signal consisted of a single short duration peak reading. The fifth area, where two concentrations of 0.18 ppb were recorded at the beginning of two adjacent lines on two separate days, was located in the extreme southeast corner of the study area. None of the results can, however, be conclusively shown to indicate the presence of elevated tracer concentrations.

5.4 Nutrient Analyses

The results of the nutrient analyses of the 36 samples collected are summarized in Table 5-3. The sample numbers correspond to those shown in Figure 4-3. Maps of the location and values of each nutrient sample are presented in Appendix C. Figures 4-2 and 4-3 show the respective location of the reference stations and of the water samples collection stations within the study area.

At the northeast corner of the study area, in shallow water close to the shore, a single nitrate-nitrite (NO3) concentration of 0.19 μM was recorded. Another high concentration of 0.11 μM was recorded near the mouth of Honokawai Stream. These values were significantly higher than the mean value of 0.042 μM. Nearly all other values were within 0.01 μM of the mean value.

TABLE 5-3. RESULTS OF NUTRIENT AND SALINITY ANALYSES

Station Sample ID	PO4 (µM)	NO3 (µM)	NH4 (µM)	SI (µM)	DOP (µM)	DON (µM)	TDP (µM)	TDN (µM)	SALINITY (o/oo)
WS-1	0.03	0.02	0.00	1.25	0.38	5.64	0.41	5.66	34.767
WS-2	0.05	0.04	0.09	1.66	0.27	5.97	0.32	6.10	34.821
WS-3	0.03	0.07	0.20	1.43	0.27	6.04	0.30	6.31	34.831
WS-4	0.04	0.02	0.04	1.28	0.23	6.16	0.27	6.22	34.807
WS-5	0.06	0.04	0.04	1.20	0.22	5.52	0.28	5.60	34.789
WS-6	0.06	0.04	0.04	1.11	0.21	5.47	0.27	5.55	34.711
WS-7	0.06	0.04	0.08	1.32	0.13	5.51	0.19	5.63	34.706
WS-8	0.06	0.04	0.07	1.33	0.21	5.56	0.27	5.67	34.708
WS-9	0.05	0.03	0.07	1.11	0.22	5.51	0.27	5.61	34.693
WS-10	0.06	0.04	0.09	1.04	0.19	5.14	0.25	5.27	34.678
WS-11	0.06	0.03	0.10	1.06	0.22	5.23	0.28	5.36	34.687
WS-12	0.07	0.04	0.12	1.17	0.15	5.32	0.22	5.48	34.696
WS-13	0.06	0.03	0.10	1.12	0.22	6.13	0.28	6.26	34.678
WS-14	0.05	0.03	0.12	1.18	0.22	6.30	0.27	6.45	34.663
WS-15	0.07	0.05	0.13	1.22	0.18	5.39	0.25	5.57	34.694
WS-16	0.06	0.05	0.08	1.28	0.23	5.78	0.29	5.91	34.687
WS-17	0.07	0.04	0.11	1.27	0.22	5.39	0.29	5.54	34.683
WS-18	0.07	0.05	0.15	1.49	0.23	5.27	0.30	5.47	34.646
WS-19	0.06	0.04	0.13	1.79	0.24	5.58	0.30	5.75	34.631
WS-20	0.06	0.04	0.12	1.34	0.23	6.34	0.29	6.50	34.646
WS-21	0.07	0.05	0.11	2.21	0.21	5.69	0.28	5.85	34.617
WS-22	0.07	0.06	0.11	1.41	0.20	6.15	0.27	6.32	34.654
WS-23	0.06	0.05	0.13	1.24	0.25	5.79	0.31	5.97	34.663
WS-24	0.06	0.03	0.11	1.11	0.21	5.40	0.27	5.54	34.655
WS-25	0.05	0.04	0.16	2.21	0.21	5.52	0.26	5.72	34.612
WS-26	0.06	0.05	0.13	3.49	0.24	5.73	0.30	5.91	34.531
WS-27	0.06	0.11	0.14	3.02	0.20	5.64	0.26	5.89	34.550
WS-28	0.04	0.01	0.17	2.97	0.21	5.78	0.25	5.96	34.599
WS-29	0.05	0.01	0.15	2.01	0.20	5.40	0.25	5.56	34.620
WS-30	0.05	0.19	0.14	4.80	0.23	5.79	0.28	6.12	34.429
WS-31	0.04	0.01	0.19	1.18	0.28	5.92	0.32	6.12	34.650
WS-32	0.05	0.02	0.20	1.09	0.25	5.99	0.30	6.21	34.640
WS-33	0.06	0.03	0.15	1.11	0.23	5.87	0.29	6.05	34.635
WS-34	0.07	0.02	0.20	1.26	0.23	5.83	0.30	6.05	34.646
WS-35	0.05	0.02	0.14	1.12	0.31	5.98	0.36	6.14	34.644
WS-36	0.05	0.03	0.17	1.16	0.28	5.49	0.33	5.69	34.639

Limits of Detection: PO4 = 0.01 µm; NO3, NH4 = 0.03 µm; Si = 0.20 µM; TDN = 0.2 µM; TDP = 0.02 µM; SALINITY = 0.0003 ppt.

Total dissolved nitrogen (TDN), and dissolved organic nitrogen (DON) concentrations were less variable with means of 5.861 and 5.701 μM, respectively. The maximum values of 6.50 and 6.34 μM also occurred at the northeast corner of the study area, although concentrations greater than 6.00 μM were recorded at the southern edge of the study area.

Dissolved silica concentrations were consistently higher close to the shore; the highest reading (4.80 μM) was in the northeast corner of the study area. The mean value was 1.58 μM.

Salinity concentrations were lowest at the northeast corner of the study area (34.439 ppt), and highest along the western edge of the area, in deep water. The maximum value was 34.831 ppt and the mean was 34.667 ppt.

Phosphorus (PO4) concentrations showed no spatial trends. The maximum value of 0.07 μM was recorded at several locations. The mean concentration was 0.056 μM. Total dissolved phosphorus (TDP) and dissolved organic phosphorus (DOP) concentrations were highest at a single location at the southwest corner of the study area (0.41 and 0.38 μM, respectively. Mean values were calculated at 0.284 and 0.228 μM, respectively.

Ammonium-nitrogen concentrations varied from a minimum of 0.0 μM at the southwest corner to a maximum of 0.20 μM, approximately 1,000 m further north, along the western edge of the study area. The mean value was calculated to be 0.119 μM.

A simple statistical summary of the results are presented in Table 5-4. Correlation coefficients were calculated to determine if a linear relationship exists between any of the parameters. For each combination of nutrient, salinity, and depth, a correlation coefficient was calculated, as well as the associated significance level. Table 5-5 shows the correlation matrix, with the coefficient shown as the top value and the significance level as the bottom value of each pair. Those coefficients with a significance value of 0.05 or less were judged to be significantly different from zero and therefore less likely to occur by chance. Obvious correlations are evident between the phosphorus compounds and between the nitrogen compounds. The expected correlation between salinity and depth and the inverse correlation between salinity and silicon (essentially a freshwater marker) occur. A correlation between silicon and nitrate-nitrite is also highly probable, although the inverse correlation between salinity and nitrate-nitrite is not quite as strong.

TABLE 5-4. SIMPLE STATISTICS OF COLLECTED SAMPLES

Variable	Code	N	Minimum	Maximum	Mean	Std Dev
Water depth (m)	**DEPTH**	36	3	70	31.9	19.0
Ortho-phosphate (μM)	**PO4**	36	0.03	0.07	0.056	0.011
Nitrate-nitrite (μM)	**NO3**	36	0.01	0.19	0.042	0.031
Ammonium-nitrogen (μM)	**NH4**	36	0.000	0.200	0.119	0.048
Dissolved silica (μM)	**SI**	36	1.040	4.800	1.584	0.810
Dissolved organic phosphorus (μM)	**DOP**	36	0.13	0.38	0.228	0.043
Dissolved organic nitrogen (μM)	**DON**	36	5.14	6.34	5.701	0.310
Total phosphorus (μM)	**TDP**	36	0.19	0.41	0.284	0.037
Total nitrogen (μM)	**TDN**	36	5.27	6.50	5.861	0.323
Salinity (0/00)	**SALINITY**	36	34.429	34.831	34.6668	0.0777

TABLE 5-5. CORRELATION MATRIX OF DEPTH, NUTRIENTS, AND SALINITY

	DEPTH	PO4	NO3	NH4	SI	DOP	DON	TDP	TDN	SALINITY
DEPTH	1.0000	-0.1872	-0.2167	-0.4778	-0.5751	0.2299	0.0920	0.2095	-0.0035	0.8636
	0.0000	0.2742	0.2042	0.0032	0.0002	0.1773	0.5934	0.2200	0.9840	0.0001
PO4	-0.1872	1.0000	0.1159	-0.0253	-0.0993	-0.5996	-0.3311	-0.3989	-0.3101	-0.2375
	0.2742	0.0000	0.5009	0.8834	0.5647	0.0001	0.0485	0.0159	0.0656	0.1630
NO3	-0.2167	0.1159	1.0000	0.0548	0.6935	-0.1415	0.0019	-0.1288	0.1074	-0.4691
	0.2042	0.5009	0.0000	0.7509	0.0001	0.4104	0.9910	0.4543	0.5332	0.0039
NH4	-0.4778	-0.0253	0.0548	1.0000	0.2143	0.0003	0.1626	-0.0069	0.3093	-0.4479
	0.0032	0.8834	0.7509	0.0000	0.2094	0.9986	0.3433	0.9680	0.0664	0.0062
SI	-0.5751	-0.0993	0.6935	0.2143	1.0000	-0.0672	0.0314	-0.1056	0.1294	-0.7003
	0.0002	0.5647	0.0001	0.2094	0.0000	0.6968	0.8556	0.5398	0.4520	0.0001
DOP	0.2299	-0.5996	-0.1415	0.0003	-0.0672	1.0000	0.3156	0.9731	0.2891	0.1603
	0.1773	0.0001	0.4104	0.9986	0.6968	0.0000	0.0608	0.0001	0.0873	0.3502
DON	0.0920	-0.3311	0.0019	0.1626	0.0314	0.3156	1.0000	0.2663	0.9837	0.0560
	0.5934	0.0485	0.9910	0.3433	0.8556	0.0608	0.0000	0.1165	0.0001	0.7455
TDP	0.2095	-0.3989	-0.1288	-0.0069	-0.1056	0.9731	0.2663	1.0000	0.2419	0.1153
	0.2200	0.0159	0.4543	0.9680	0.5398	0.0001	0.1165	0.0000	0.1552	0.5032
TDN	-0.0035	-0.3101	0.1074	0.3093	0.1294	0.2891	0.9837	0.2419	1.0000	-0.0582
	0.9840	0.0656	0.5332	0.0664	0.4520	0.0873	0.0001	0.1552	0.0000	0.7361
SALINITY	0.8636	-0.2375	-0.4691	-0.4479	-0.7003	0.1603	0.0560	0.1153	-0.0582	1.0000
	0.0001	0.1630	0.0039	0.0062	0.0001	0.3502	0.7455	0.5032	0.7361	0.0000

An analysis of variance, (ANOVA) was performed to test for statistically significant differences between sample groups divided by depth and reference site for each of the parameters measured. Each sample collected from the study area was placed into one of three depth groups (0 - 10 m; 11 - 40 m; 41- 70 m) and the six reference samples constituted a fourth group (Table 5-6). For each parameter that had an overall significance between groups, a multiple comparison of means was performed to test for differences between the means of specific groups. Table 5-7 summarizes the statistically significant differences of the means for the four groups. The results indicated that statistically significant differences existed within some of the depth groups and between the reference group and some of the depth groups, at a significance value of 0.05. The detailed results of the analysis of variance and the comparison of group means are shown in Appendix D.

Only small relative increases in nutrient concentrations could be attributed to the effluent if a dilution factor of 3,200 was applied to the reported LWRF effluent concentrations (Table 5-8). The greatest relative increase occurred with the nitrate-nitrite (NO3) level, which would increase 1.21 times the average background level to 0.09 µM. The next highest relative increase would occur with dissolved silica (SI), at 0.31 times the average background concentration, to a value of 2.06 µM. All other calculated increases in nutrient levels were less than 12 percent of the measured background level in the study area. The greatest calculated increase, in nitrate-nitrite concentrations to 0.09 µM, remained within the reported range for mid- to low-latitude Pacific surface waters (Broecker and Peng, 1982).

No correlation in spatial patterns between the elevated nutrient values and the possible elevated fluorescence concentrations can be discerned. Values for all nutrient concentrations recorded in the vicinity of the reported freshwater seeps at the southeast corner of the study area were close to background levels. However, the nutrient data were collected on a single day at only 30 locations within the study area, which was a much less extensive coverage than supplied by the fluorometry data. Thus the use of the nutrient data as a comparison of spatial patterns of elevated fluorescence is limited.

5.5 Water Column Profiles

Data was plotted for each of the 22 CTD casts and graphs of density, temperature, and salinity versus depth for each cast are included in Appendix E. Figures 4-2 and 4-4 show the relative location of each CTD cast. For each cast, data collection began at the surface and continued until the instrument hit the bottom. The maximum depth of each plot is equivalent to the water depth at that sampling location. Figure 5-12 shows an example of the plotted data for Station CTD 3-2. The data recorded at this location represent the greatest range measured for each parameter during the study.

TABLE 5-6. SAMPLE GROUPING FOR ANOVA OF NUTRIENT AND SALINITY DATA

	Sample Grouping			
	Reference	**0 - 10 m**	**11 - 40 m**	**41 - 70 m**
Sample ID	WS-31	WS-19	WS-6	WS-1
	WS-32	WS-25	WS-7	WS-2
	WS-33	WS-26	WS-8	WS-3
	WS-34	WS-27	WS-9	WS-4
	WS-35	WS-28	WS-10	WS-5
	WS-36	WS-29	WS-11	WS-13

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TABLE 5-7. SUMMARY OF COMPARISON OF MEANS OF GROUPS OF NUTRIENT AND SALINITY DATA

Parameter	Groups with significantly different means (confidence level of 0.95)
PO4 *ortho-phosphate*	11-40 m & 41-70 m
NO3 *nitrate-nitrite*	-
NH4 *ammonium-nitrogen*	Ref & 11-40 m Ref & 41-70 m
SI *dissolved silica*	0-10 m & 11-40 m 0-10 m & 41-70 m 0-10 m & Ref
DOP *dissolved organic phosphorus*	Ref & 11-40 m
DON *dissolved organic nitrogen*	-
TDP *total dissolved phosphorus*	Ref & 11-40 m
TDN *total dissolved nitrogen*	-
SALINITY *salinity*	0-10 m & 11-40 m 0-10 m & 41-70 m Ref & 41-70 m

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TABLE 5-8. COMPARISON OF NUTRIENT CONCENTRATIONS

Parameter	**Ce** Measured LWRF Effluent Concentration* (mM)	**Co** Measured Ocean Concentration (μM)	**Cm** Maximum Concentration after Dilution and Mixing** (μM)	**(Cm-Co)/Co** Relative Increase in Background Concentration
NO3	163	0.04	0.09	1.21
NH3	11	0.12	0.13	0.03
TDN	779	5.86	6.10	0.04
TDP	110	0.28	0.32	0.12
Si	155	1.58	2.06	0.31

* Flow-weighted average from LWRF samples collected 5/22/92
** Assuming maximum dilution of 3,200

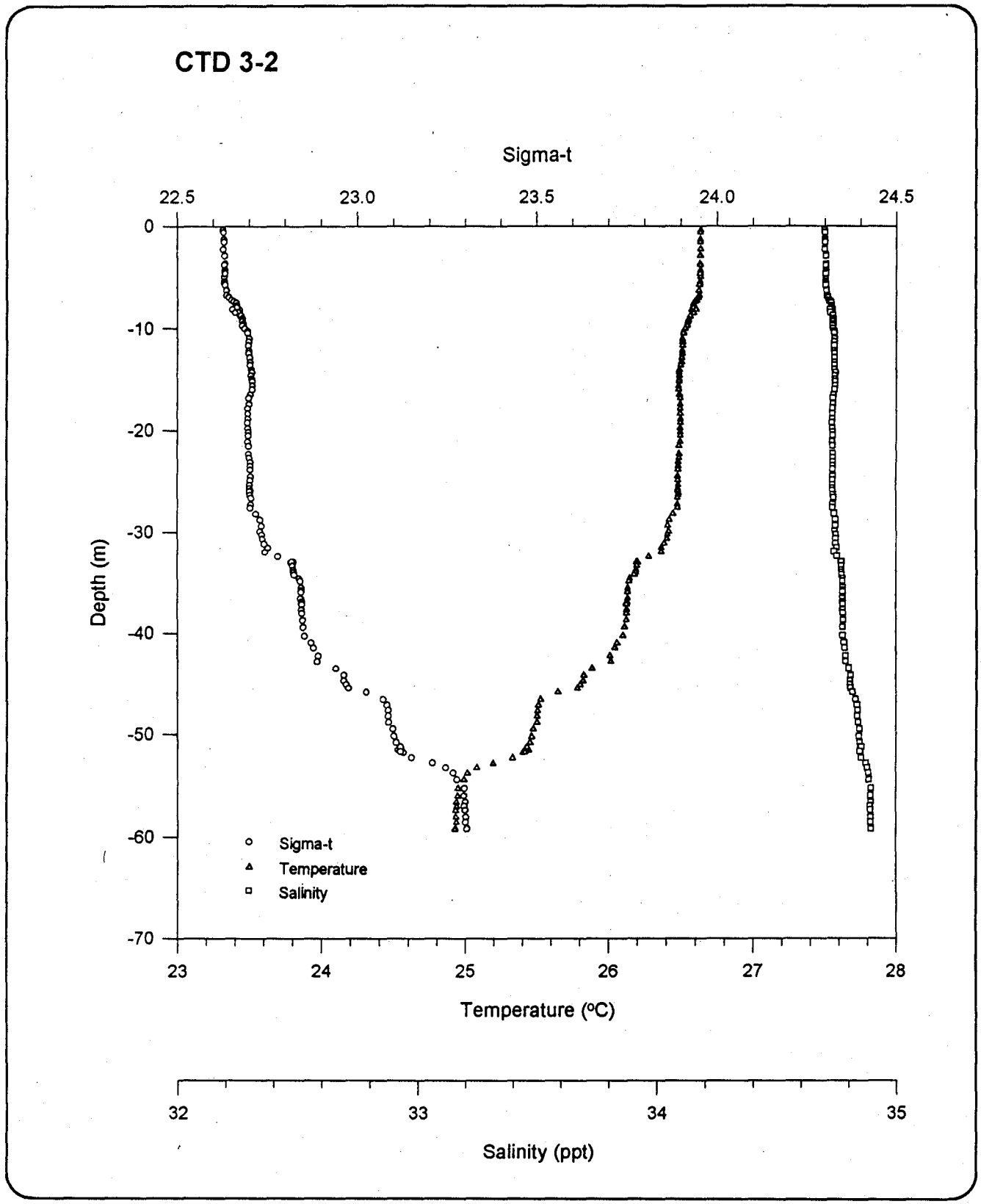

Figure 5-12. Example of water column profile from CTD data.

Salinity varied by no more than 0.2 ppt (0.6 percent of the surface value) throughout the water column at any station except in the northeast corner of the study area, where a minimum of 33.5 ppt was recorded in the surface two meters. The maximum temperature variation within the water column was less than 1.5 °C. The upper 30 m exhibited near constant values, followed by a slow decrease of 1.0 °C to 1.5 °C between depths of 30 m and 55 m. In nearly all cases, the density plot, presented as a sigma-t value, ([density - 1] x 10^{-3}), is a reflection of the temperature plot, indicating that the water density is strongly influenced by temperature and the salinity has only a small effect.

The temperature data from the CTD profiles correspond with the data recorded by the fluorometer, which are presented in Appendix A as plots of temperature versus time for each of the transects. The lower temperatures indicate the time the submersible pump was pumping water from the bottom, the higher temperatures indicate when the pump was at depths of less than 30 m, which occurred as the survey vessel moved between sampling stations.

The data from both the CTD casts and the fluorometer temperature records suggest that the water column within the study area is well mixed to the maximum depth in the study area, 60 m to 70 m, and no significant thermocline or pycnocline was present. This suggests the formation of a trapping layer did not occur within the study area during the period of the study and influx of effluent from the seafloor would not be constrained to depth by the density or temperature characteristics of the water column.

5.6 Post-Survey Sampling Results

Eighty discrete, near-bottom water samples were collected from ten locations over a 2-month period. Table 5-9 lists the discrete sampling positions; Figure 4-5 shows the relative position of the sampling points within the study area. In addition to the samples collected in the study area, two background samples were collected off Kekaa Pt., 3,500 m (1.5 nm) south of the study area.

The samples were analyzed within 5 days of collection. The laboratory fluorometer, although a different model, was of similar accuracy (0.02 ppb), sensitivity (0.02 ppb), and resolution (0.002 ppb) as the field fluorometer. A calibration was performed immediately before each analysis. No temperature compensation device was available for the fluorometer, so all standards and blanks were allowed to come to room temperature (between 20 - 23 °C) before each analysis. Because the temperature of the sample increases when placed in the fluorometer, no sample was reanalyzed for a minimum of 1 hr after the initial reading.

For each of the eight analyses, the range of reported sample concentrations was about 0.02 ppb, similar to the sensitivity of the instrument, and also similar to the range between the two background samples. The average valve for each analysis of the ten samples varied by 0.029 ppb, from -0.016 to 0.013 ppb. The negative values are a result of the instrumental variation when measuring concentrations about zero, and do not imply that negative concentrations were measured. Standard deviations for each of the eight sets of analyses are less than 0.007 and indicate a small spread in the measured concentrations (Table 5-10). Average concentrations for each of the ten samples, measured over the 2-month period, are less than 0.007 ppb, which is also less than the sensitivity of the instrument.

All recorded concentrations were close to zero and most were less than the detection limit of the instrument. These results indicated that if the tracer was present in the samples, the concentrations were less than 0.02 ppb.

5.7 Summary of Results

During the study period, July 1 to August 31, 1993, a daily average volume of 5.6 million gallons was treated at the LWRF. Of this amount, an average of 3.0 mgd was injected into Well No. 2. The average concentration of active Rhodamine WT tracer mixed with the effluent at Well No. 2 was 122 ppb, or 63 ppb if the total effluent of the LWRF is assumed to be mixed completely after injection. These concentrations are adjusted for an estimated maximum loss of 10 percent of the active tracer over a residence time of 60 days in the ground water, due to oxidation from residual chlorine in the treated effluent or other uncontrolled losses, such as adsorption.

Over 60 hours of data collection was carried out within the 1.5 nm by 1.5 nm study area. Measurements of depth, fluorescence, and temperature at over 420 near-bottom sampling locations were recorded. The sampling locations were nominally 200 m apart along each transect and the transects were spaced 100 m apart. Discrete, near-bottom water samples were collected at 30 locations within the Study Area and at six reference locations. Laboratory analyses for nutrient concentrations and salinity were performed on these samples. Water column profiles of temperature, conductivity (salinity), and depth were collected at 22 of the 36 sampling locations. Discrete water samples were collected from ten locations throughout the study area for a period of one to three months after the fluorometric survey was completed.

Maximum depths of 60 to 70 m were recorded approximately 1.5 nm offshore, at the western edge of the study area. A flat area of 40- to 45-m depth is apparent through the center of the area. A relatively steep rise from 40 to 10 m occurs between 100 and 500 m from the shoreline.

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TABLE 5-9. POSITION OF POST-SURV

Station No.	N Latitude		
S1	20:56:20	156:41:36	4
S2	20:57:06	156:41:29	5
S3	20:56:25	156:42:31	40
S4	20:56:45	156:42:10	40
S5	20:57:30	156:41:49	15
S6	20:56:35	156:43:12	50
S7	20:57:07	156:42:36	40
S8	20:57:53	156:42:08	40
S9	20:57:04	156:43:07	70
S10	20:57:59	156:42:39	60

TABLE 5-10. MEASURED CONCENTRATIONS (ppb) OF POST-SURVEY SAMPLES

Sample No.	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	Ref	Range	Average	Std Dev
Date														
10-Oct	0.002	0.000	0.000	0.002	-0.004	-0.012	0.008	0.008	0.012	0.000		0.024	0.002	0.007
15-Oct	-0.017	-0.015	-0.009	-0.015	-0.015	-0.011	-0.017	-0.013	-0.023	-0.025		0.016	-0.016	0.005
23-Oct	-0.019	-0.013	-0.011	-0.015	-0.015	-0.015	-0.009	-0.007	-0.015	-0.013		0.012	-0.013	0.003
30-Oct	0.006	0.004	0.004	0.016	0.022	0.010	0.022	0.010	0.012	0.020	0.011	0.018	0.012	0.007
7-Nov	-0.003	-0.011	-0.009	-0.011	-0.009	-0.009	-0.011	-0.013	-0.013	-0.009		0.010	-0.010	0.003
16-Nov	0.012	0.012	0.007	0.014	0.012	0.008	0.007	0.007	0.012	0.008		0.007	0.010	0.003
2-Dec	-0.018	-0.016	-0.014	-0.016	-0.016	-0.014	-0.012	-0.016	-0.014	-0.016		0.006	0.010	0.003
8-Dec	-0.001	0.005	0.007	-0.003	0.003	0.003	0.003	0.005	0.001	-0.003	-0.003	0.010	-0.015	0.002
Maximum	0.012	0.012	0.007	0.016	0.022	0.010	0.022	0.010	0.012	0.020	0.011			
Average	-0.005	-0.004	-0.003	-0.004	-0.003	-0.005	-0.001	-0.002	-0.004	-0.005	0.004			
Std Deviation	0.012	0.011	0.009	0.013	0.014	0.010	0.013	0.011	0.014	0.014	0.010			

Nutrient analyses showed some small differences between samples collected at different depths and between the reference samples and the study samples. No correlation between the occasional elevated nutrient concentrations and the spacial distribution of fluorescence could be identified. Water column profile data showed nearly constant salinity with depth and approximately one degree Celsius temperature variation between the surface and bottom. These data indicated that the water was well mixed and no thermocline or trapping layer was present.

Background fluorescence concentrations varied between 0.04 and 0.06 ppb within the study area and at the reference stations. Concentrations between 0.01 and 0.3 ppb were recorded frequently in near-bottom water during the first half of the survey, but after investigation these readings were attributed to a light backscattering effect, a result of sand and smaller particles passing through the fluorometer. This source of interference was eliminated in the second half of the survey by installing two extra filters in the water intake line. Once the filters were installed, few concentrations above 0.01 ppb were recorded.

Concentrations of near-bottom fluorescence generally fell within the range of the background variations, resulting in data with a small signal-to-noise ratio. Statistical analyses and contouring of the data identified five possible areas of elevated concentrations. However, at three of the areas the magnitude of the concentrations was close to the sensitivity limit of the fluorometer. The fourth signal, although stronger, was a single reading of short duration. The fifth area, in the southeast corner of the study area was three times the background concentration and was recorded at adjacent locations on two different days in shallow water, close to where freshwater seeps and bubbles had been previously reported. The location is at the boundary of the study area and no data are available to the south. Further investigation would be required in this area to confirm the presence of elevated tracer and effluent concentrations.

The estimated detection limit of the fluorometer was 0.02 ppb. For tracer to be present and undetectable in the sampled water, it would have undergone dilutions of at least 3,200 to 5,900 times.

The following conclusions can be drawn from the collected data:

- Tracer may have been detected at concentrations of between 0.08 and 0.18 ppb at five small areas within the study area, but the data did not conclusively show the presence of tracer at any of these locations. This was because the elevated readings were either close to the detection limit of the fluorometer, or because the elevated readings were isolated

events of short duration. No correlation is evident between the fluorometric survey results and the nutrient analyses or the long-term post-survey fluorescence analyses. Further sampling would be required at each of the five locations to verify the presence of elevated effluent concentrations.

- At all other areas within the study area, the tracer was not detected. For the tracer to be present and undetectable, the tracer and the effluent must have undergone dilutions of between 3,200 and 5,900 times the injection concentrations. If the tracer was present at detectable levels, it was diluted below detection concentrations before reaching any sampling points, or it was not present during times that sampling was being conducted at that area. That is, if it was present in the near-bottom water, the tracer had been diluted to undetectable concentrations vertically within the first 10 to 30 cm of the bottom, or horizontally within 100 to 200 m of its seabed source.

- The probability of tracer entering the coastal waters within the study area as a single plume is very low. It is more likely that if the tracer was present, it influxed through a large number of discrete points or through one or more wide-area seeps at low flow rates and was diluted to nondetectable concentrations rapidly and within short distances, both horizontally and vertically, from the point(s) of influx.